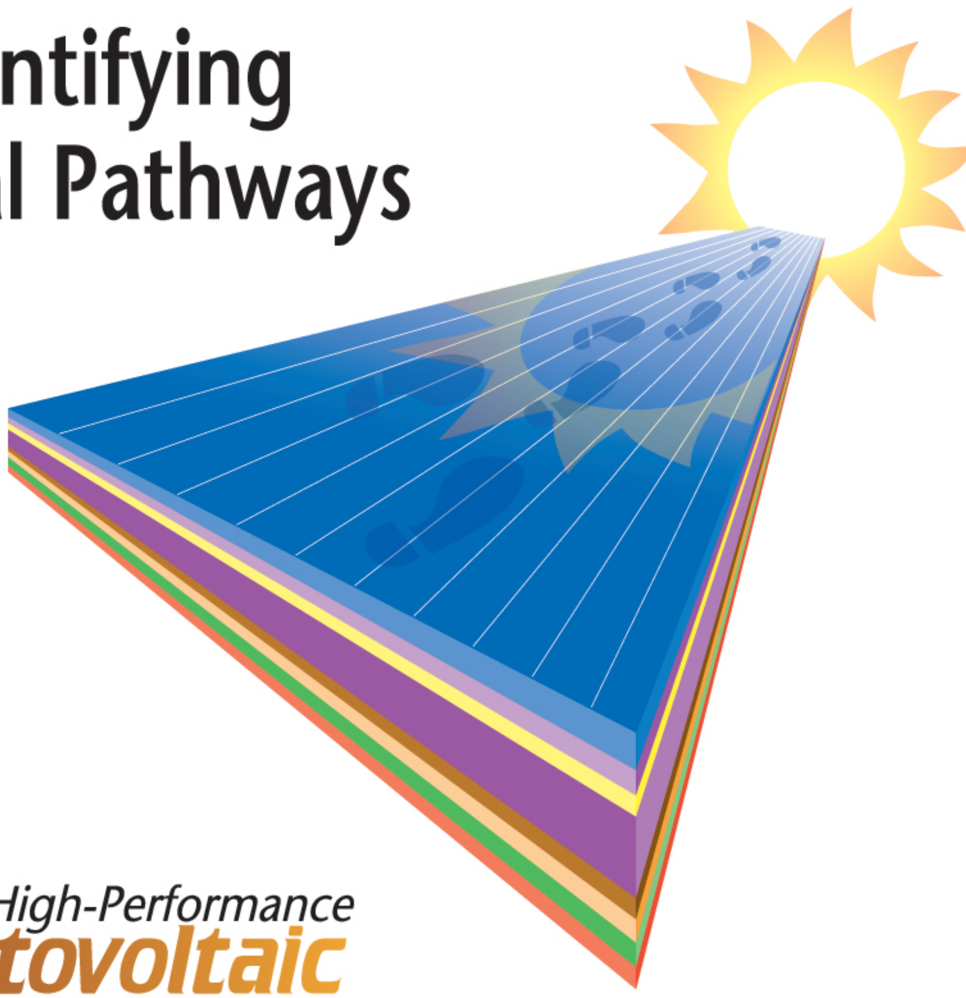
High-Performance Photovoltaic Project

Kickoff Meeting

NREL • October 18, 2001

Identifying Critical Pathways



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NREL / BK-520-31284

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Identifying Critical Pathways

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393

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KICKOFF MEETING AGENDA

8:00-8:10	Martha Symko-Davies, National Renewable Energy Laboratory Welcome
8:10-8:25	Tim Coutts, National Renewable Energy Laboratory "Realistic Modeling of Thin-Film Tandem Solar Cells"
8:25-8:40	William Shafarman, University of Delaware "Wide Band Gap $Cu(InGa)(SeS)_2$ and (CdZn)Te Thin Films for Tandem Solar Cells"
8:40-8:55	David Young, National Renewable Energy Laboratory "NCPV Thin-Film Tandem Research"
8:55-9:10	Akhlesh Gupta, University of Toledo "II-VI Tunnel Junctions and Absorber Alloys by Magnetron Sputtering"
9:10-9:25	Ingrid Eisgruber, Global Solar "Progress Toward 20% Efficient $CuIn_xGa_{1-x}Se_2$ Photovoltaic Devices on Foil Substrates"
9:25-9:40	Doug Rose, First Solar LLC "High Performance PV Tasks at First Solar"
9:40-9:55	Chris Ferekides, University of South Florida "II-VI Based High Band Gap Devices for Tandem Applications"
9:55-10:10	Oscar Crisalle, University of Florida "CGS/CIGS Tandem Cells: Critical Manufacturing Issues"
10:10-10:25	Break
10:25-10:40	Angus Rockett, University of Illinois "$CuInSe_2$ Heterojunctions and Heterojunction Solar Cells With GaAs and Ge"
10:40-10:55	Michael Mauk, AstroPower, Inc. "InGaP/GaAs-on-Ceramic Thin-Film Monolithically Interconnected, Large Area, Tandem Solar Cell Array"
10:55-11:10	Sarah Kurtz, National Renewable Energy Laboratory "NREL Basic Research Toward a 40% Efficiency"
11:10-11:25	Keith Emery, National Renewable Energy Laboratory "Reference Conditions for PV Concentrators"

11:25-11:40	Raed Shariff, Spectrolab, Inc. "High Performance, Low Cost III-V PV Concentrator Module"
11:40-11:55	Mark O'Neil, ENTECH, Inc. "Development of Terrestrial Concentrator Modules Using High-Efficiency Multi-Junction Solar Cells"
11:55-12:10	Mark Stan, Emcore "A Three-Junction Solar Cell for High Concentration Applications".
12:10-12:30	Break
12:30-1:30	Discussion

Topics:
1) Sharing/coordinating of information
2) Website
3) Logistics - Meeting, when, where, and how often
4) Report at end of Phase I
5) Nonstructured group meetings - inclusive for next phase??

High-Performance Photovoltaic Project

Kickoff Meeting

Identifying Critical Pathways

Martha Symko-Davies

National Center for Photovoltaics • National Renewable Energy Laboratory

October 18, 2001

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High-Performance Photovoltaic Project

Near Term Key Targets	Date
Demonstrate a 20% Efficiency Thin Film Cell under Low Concentration	2001
Identify Key Issues and Pathways for Achieving a 33% Concentrator Module and a 25% Thin Film Multijunction Cell	2002
Demonstrate a 34% Cell under Concentration	2003
Full Implementation of Thin Film Process Integration	2004
Fabricate a Dual-Junction Thin Film polycrystalline Cell of 15% efficiency	2005

Demonstrate Polycrystalline Dual-Junction Thin Film Cell of 25% Efficiency

Demonstrate a 40% Cell under Concentration

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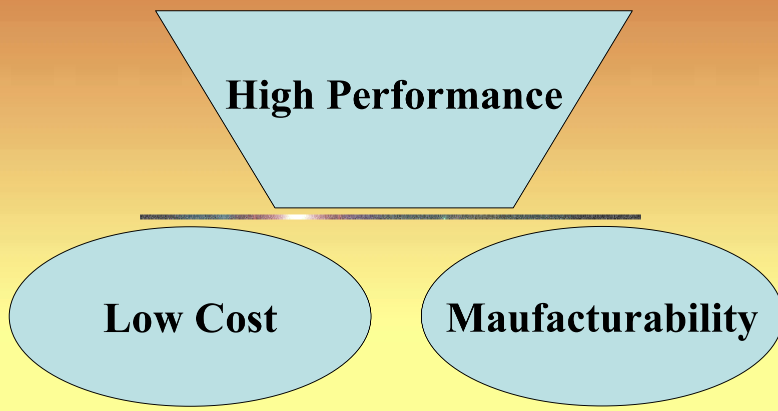
What Makes this Program Different??



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Purpose of Meeting????

Avenue to meet and introduce yourself to others in this project

Basis for **sharing** information and **collaboration**

Discussion Topics

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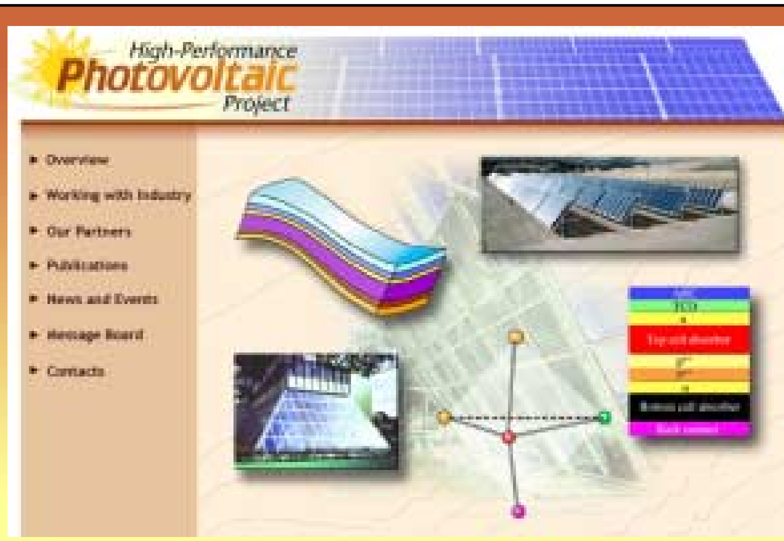

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High Performance PV subcontractors Polycrystalline

Subcontractor	Title
*Astropower	InGaP/GaAs-on Ceramic Thin-Film Monolithically Interconnected, Large Area, Tandem Solar Cell Array
University of Delaware	Thin Film Multijunction Solar Cells: Development of a High Bandgap Cell (CIS and CdTe alloys)
University of Florida	Identification of Critical Paths in the Manufacturing of Low-Cost High-Efficiency CGS/CIS Two-Junction Tandem Cells (Single-Crystal CIS-alloy top cells on GaAs)
University of Toledo	Polycrystalline Thin-Film Tandem Photovoltaic Cells (CdTe-alloys)
University of South Florida	Development of a II-VI-Based High Performance, High Band Gap Device for Thin-Film Tandem Solar Cells(CdSe and CdTe-alloy)
Global Solar	Progresss Toward 20% Efficient $CuIn_xGa_{1-x}Se_2$ Photovoltaic Devices on Foil Substrates

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High Performance PV subcontractors Concentrators

Subcontractor	Title
Univ. of Illinois	$Cu(In,Ga)Se_2$ Heterojunction Solar Cells for Extreme High-efficiency Photovoltaic Concentrators (CIS on single-crystal GaAs for potential use in III-V multijunctions for concentrators)
Entech, Inc.	Near-Term Integration of III-V Cells Operating at 440X, Into Entech's Field Proven Concentrator Module
SunPower Corporation	Lens-Based Concentrator Modules: Exploring Critical Optical and System Integration Issues
Spectrolab, Inc.	High Efficiency, Low Cost, IIII-V Concentrator PV Cell & Receiver Module
Emcore	A Three-Junction Solar Cell for High Concentration Applications (III-V multijunctions-lattice mismatched structure)

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DiscussionTopics

1) Purpose of Meetings

2) Structure: Working Groups???

3) Meeting Logistics -when, where, and how often

4) Report at end of Phase I

5) Inclusive for next phase

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Realistic modeling of thin-film, tandem solar cells

Timothy J. Coutts, J. Scott Ward,
David L. Young, Timothy A. Gessert, and
Rommel Noufi

tim_coutts@nrel.gov

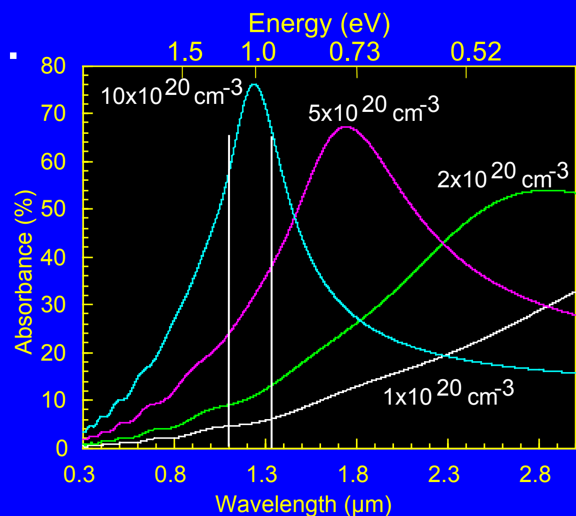
*NREL

Issues

- A transparent conducting oxide (TCO) is used in all thin-film solar cells
- Free-electrons absorb in the near-infrared portion of the spectrum
- Depending on their concentration and mobility, they can impact cell performance
- In tandem cells their effect can be large

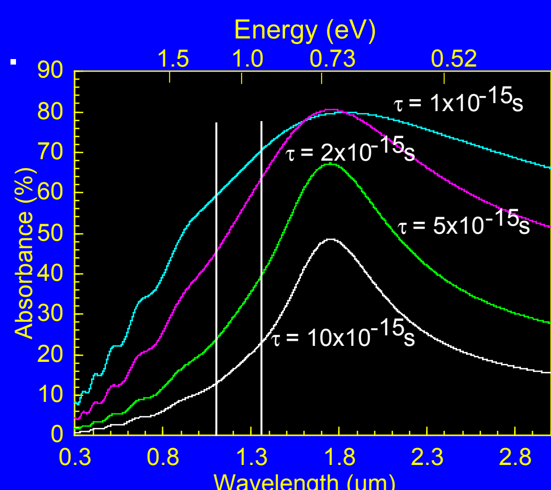
Dependence of TCO absorbance on free-carrier concentration

- t = 500 nm
- ε_∞ = 4.4
- m^* = 0.35 m_e
- τ = 5×10^{-15} s
- μ = 25 cm^2 s^{-1} V^{-1}



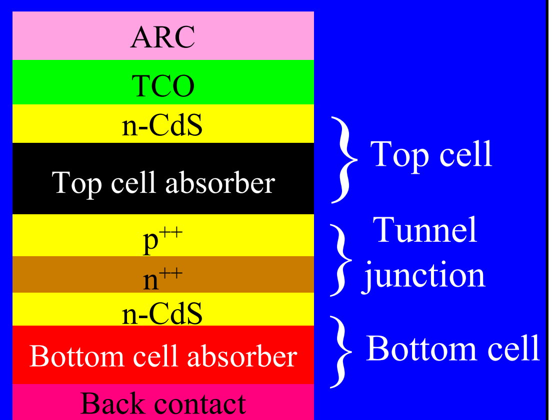
Dependence of absorbance on free-carrier relaxation time

- t = 500 nm
- n = 5×10^{20} cm^{-3}
- ε_∞ = 4.4
- m^* = 0.35 m_e
- μ = 5-50 cm^2 V^{-1} s^{-1}



Schematic of modeled thin-film tandem cell

- All interfaces assumed to be specular
- No interdiffusion
- Top p-type absorber assumed to be chalcopyrite



Assumptions and modeling approach

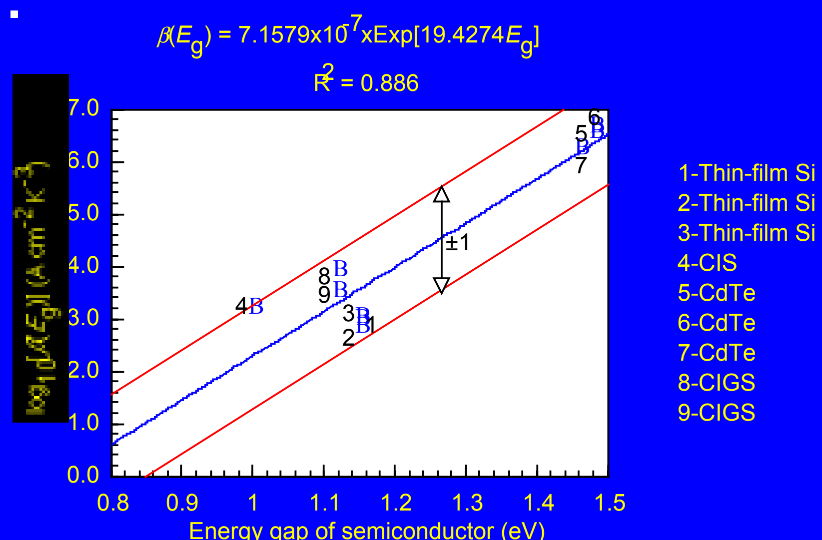
- Calculate light transmitted into the top (chalcopyrite) absorber, and, hence, J_{sc1} (Global reference spectrum)
- Assume all photons with $E_{g1} < E < E_{g2}$ contribute to J_{sc2}
- Put J_{sc} equal to the smaller of J_{sc1} and J_{sc2}
- Take ideality factor as 1.5
- Calculate J_0 from a quasi-empirical model
- Calculate $V_1(J)$, $V_2(J)$ and $V_T(J)$
- Calculate fill-factor, P_{mpp} and efficiency as f(E_{g1}, E_{g2})

Modeling of J_0

$$J_0(E_g) = \beta(E_g) T^3 \exp(-E_g/kT)$$

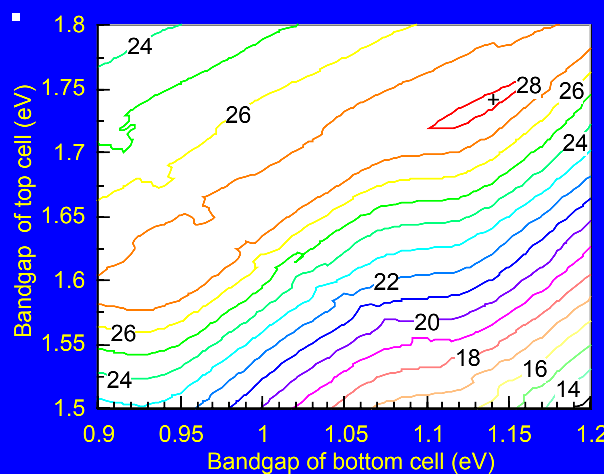
- Calculate $\beta(E_g)$ and correlate with E_g for the best single-junction thin-film devices
- This gives a reasonable estimate of $J_0(E_g)$ for devices of uninvestigated bandgaps
- It does **not** define the absolute limit

$\mathrm{Log}_{10}\beta(E_g)$ vs. E_g



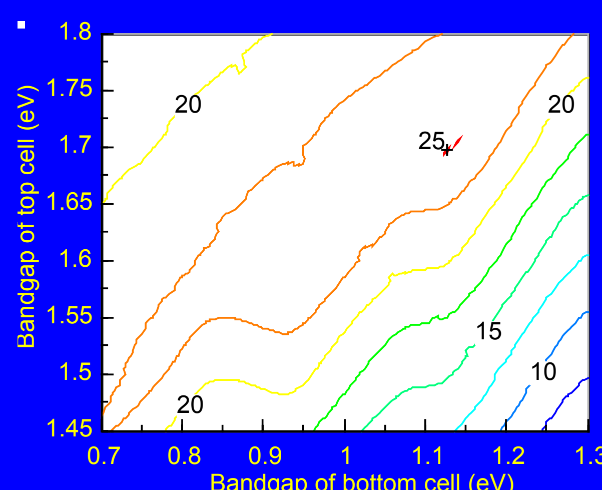
Modeled tandem efficiency (i)

- Assumes all photons reach the top absorber
- Uses central correlation line
- Absolute maximum is 28.2%



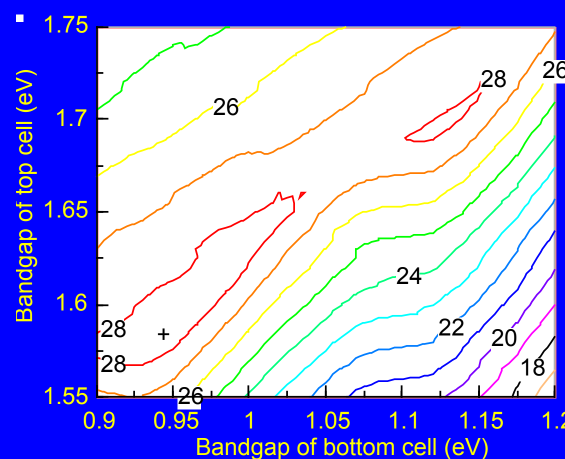
Modeled tandem efficiency (ii)

- TCO thickness = 500 nm
- $n = 1\times10^{20}$ cm^{-3} $\mu = 75$ cm^2 V^{-1} s^{-1}
- CdS thickness = 50 nm
- MgF_2 thickness = 100 nm
- Maximum efficiency = 25.0%



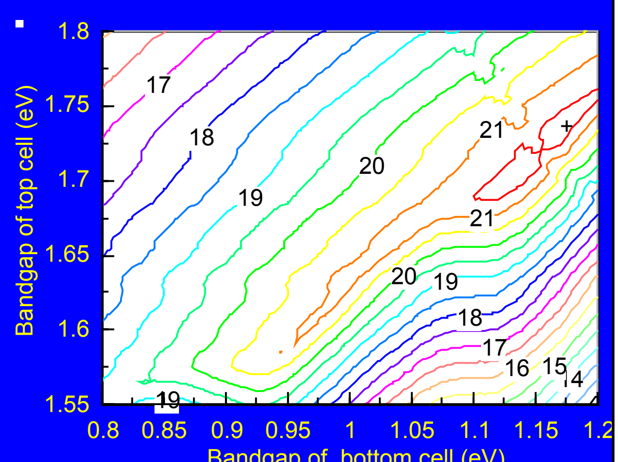
Modeled tandem efficiency (iii)

- Uses the same front layers
- Uses the lowest of the three lines in the log $\beta(E_g)$ correlation
- Maximum efficiency = 28.7%



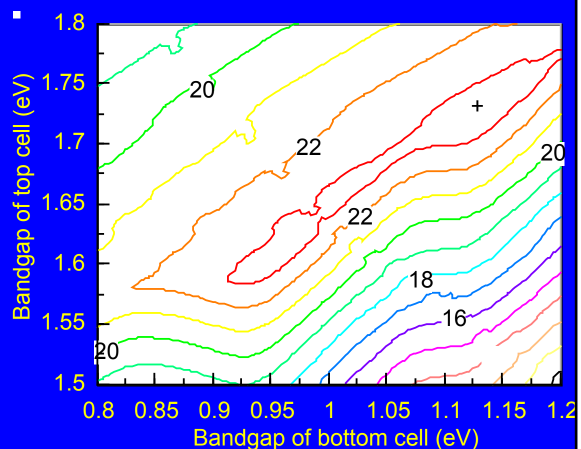
Modeled tandem efficiency (iv)

- Uses the same front layers
- Uses the upper-most of the three lines in the log $\beta(E_g)$ line
- Maximum efficiency = 21.8%



Modeled tandem efficiency (v)

- Uses a TCO with $n = 5{\times}10^{20}$ cm^{-3}, $\mu = 75$ cm^2 V^{-1} s^{-1} $t = 500$ nm
- Uses central log $\beta(E_g)$ line
- Maximum efficiency = 23.6%



Summary

- TCOs with low carrier concentration and high mobility needed to minimize free-carrier absorption
- Beneficial to eliminate the TCO and the CdS
- Depending on J_0, the optimum bandgap pair is about 1.7 and 1.13 eV
- The goal of 25% is achievable but challenging!
- Reduction in J_0 would give wider choice of materials and a higher potential maximum efficiency

What are the dominant factors?

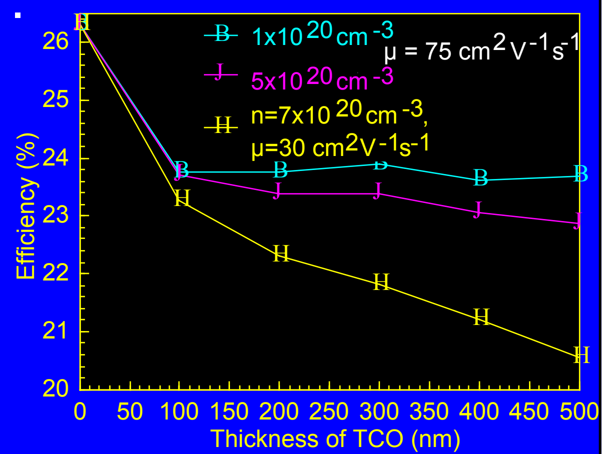
- The TCO film's optical properties are governed by Maxwell's equations
- The electron motion is described by a second order differential equation
- This was the approach used by Drude over 100 years ago

Goals of High Performance Project

- 40% laboratory demonstration of single-crystal device
  - probably monolithically grown
- 25% laboratory demonstration of thin-film polycrystalline device
  - monolithic or mechanically stacked device

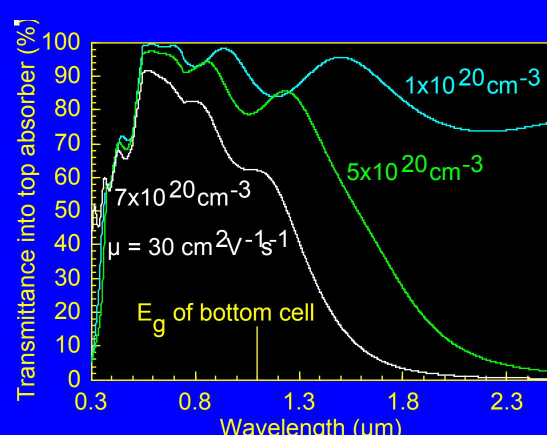
Dependence of efficiency on TCO thickness

- Always higher with lower carrier concentration
- Both high mobility materials
- Differences will increase as mobility decreases



Modeling of J_{sc}

- All TCO thicknesses are 500 nm
- μ = 75 cm^2 V^{-1} s^{-1} for n = 1 and 5×10^{20} cm^{-3}
- μ = 30 cm^2 V^{-1} s^{-1} for n = 7×10^{20} cm^{-3}
- All use 50 nm CdS and 100 nm MgF_2



Everything depends on J_0!

Wide Band Gap $CuInSe_2$- and CdTe- based Thin Films for Tandem Solar Cells

Bill Shafarman

Brian McCandless

Mario Gossla

Institute of Energy Conversion

University of Delaware

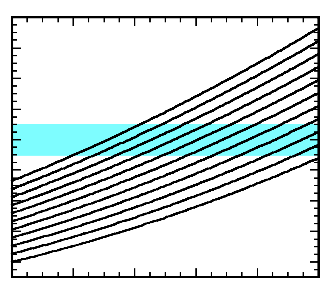
$CuIn_{1-x}Ga_x(Se_{1-y}S_y)_2$ Wide Band Gap Cells

$CuIn_{1-x}Ga_x(Se_{1-y}S_y)_2$

- **Increase E_g with minimum. cation and anion alloy concentrations.**
- **Admittance spectroscopy lower defect concentrations than $CuIn_xGa_{1-x}Se_2$ or $CuIn(Se_{1-y}S_y)_2$ films with comparable E_g**
  Friedlmeier and Schock, 2nd World Conf. PVSEC, 1117 (1997).

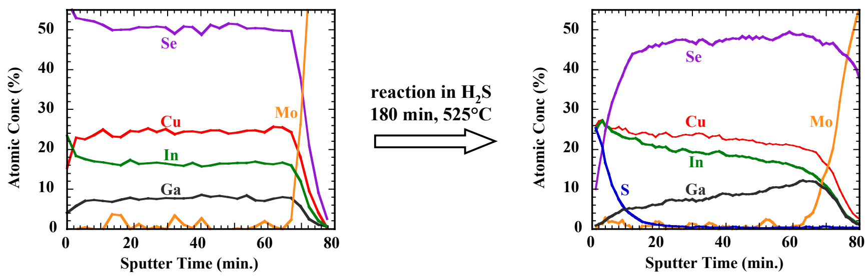
Deposition approaches

- **Se + S reaction of Cu/Ga/In precursors**
  - **Ga ends up at back of film**
  - **Requires T≈ 600°C anneal to form uniform bandgap**
    Marudachalam,et. al. Appl. Phys. Lett 67, 3978 (1995).



$CuIn_{1-x}Ga_x(Se_{1-y}S_y)_2$ Wide Band Gap Cells

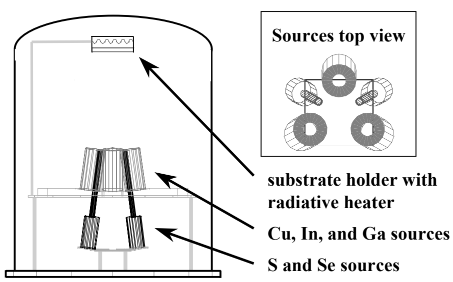
- S replacement reaction: $CuIn_{1-x}Ga_xSe_2 + H_2S \Rightarrow CuIn_{1-x}Ga_x(Se_{1-y}S_y)_2$.
  - Films reacted in combinations of flowing H_2S + Ar + O_2 at 1 atm.
  - Time to uniformly incorporate S into $CuInSe_2$:
    - ~ 1 hour for Cu-rich films. Engelmann, et. al., *Thin Sol. Films* 387, 14 (2001).
    - >> 8 hours for Cu-poor (device quality) films.
  - Ga moves to back of film (toward Mo contact).

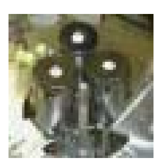


$CuIn_{1-x}Ga_x(Se_{1-y}S_y)_2$ Wide Band Gap Cells

Elemental evaporation - critical issues.

- Thermal control of Se and S evaporation sources.
  - P_{vapor} requires T > 100 - 300°C, while Cu, In, Ga at 1100 - 1400°C.
- Corrosivity of S vapor in deposition chamber and vacuum system.





CdTe-based Wide Band Gap Cells

Material selection criteria:

- Complete miscibility
- Isostructural, isoelectronic p-type
- Chemical stability (e.g., HgTe unstable at T>400°C)
- minimize perturbation from CdTe

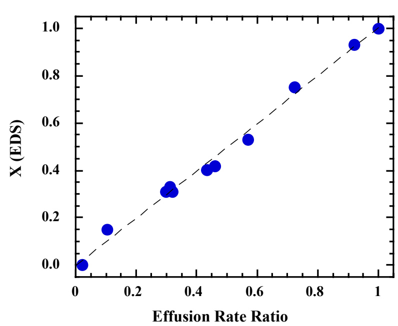
$\Big\}$ $Cd_{1-x}Zn_xTe$

Compound	E_g Range (eV)	End-Point Structure	Miscibility Gap ?
Cation Substitution			
$Cd_{1-x}Zn_xTe$	1.49 – 2.25	ZB - ZB	N
$Hg_{1-x}Cd_xSe$	0.10 – 1.73	ZB - W	N
$Hg_{1-x}Zn_xTe$	0.15 – 2.25	ZB - ZB	N
Anion Substitution			
$CdTe_{1-x}S_x$	1.49 – 2.42	ZB – W	Y
$CdTe_{1-x}Se_x$	1.49 – 1.73	ZB – W	N
$CdSe_{1-x}S_x$	1.73 – 2.42	W – W	N
$HgTe_{1-x}S_x$	0.15 – 2.00	ZB – ZB	?
$HgSe_{1-x}S_x$	0.10 – 2.00	ZB - ZB	N

$Cd_{1-x}Zn_xTe$ Wide Band Gap Cells

Deposition:

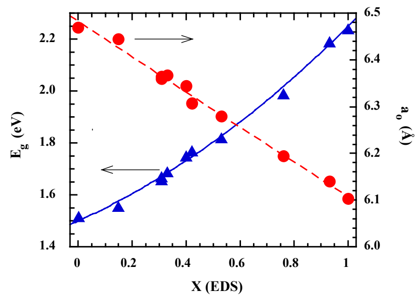
- Evaporation from CdTe and ZnTe compounds
  - Control film composition by relative effusion rate ratio $r_{ZnTe}/(r_{CdTe} + r_{ZnTe})$
  - High sticking coefficient
- T_{SS} = 325°C
- glass/ITO/CdS substrates

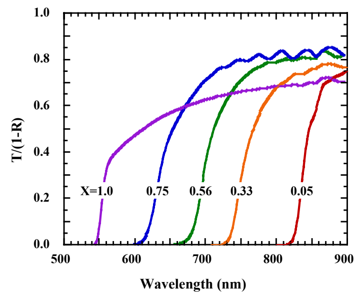


$Cd_{1-x}Zn_xTe$ Wide Band Gap Cells

$Cd_{1-x}Zn_xTe$ films have been deposited over entire composition range.

- **Optical band gap 1.5 ≤" E_g ≤ " 2.55 eV and bowing parameter b = 0.3.**
- **Single phase films with linear variation in lattice parameter a_o determined from x-ray diffraction.**
- **Sub-E_g optical transmission = 70 - 90% over target band gap range.**





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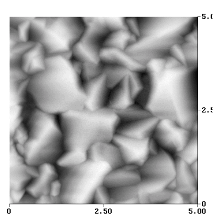
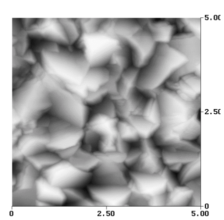
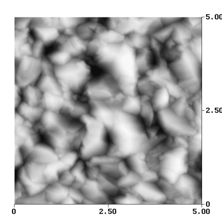
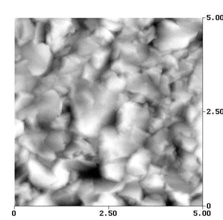
$Cd_{1-x}Zn_xTe$ Morphology: T_{SS} = 325°C

41110	41112	41111	41113
d = 3.8 μm	d = 4.0 μm	d = 2.8 μm	d = 3.5 μm
rms ~ 33 nm	rms ~ 35 nm	rms ~ 34 nm	rms ~ 21 nm
x ~ 0.05	x ~ 0.10	x ~ 0.30	x ~ 0.45









- **Faceted morphology**
- **Grain size ↓ as x ↑**
- **RMS constant until x ~ 0.45**

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Transparent back contact for $CuIn_{1-x}Ga_xSe_2$

Requirements for contact include:

- chemical stability in Se atmosphere
- ohmic contact
- adhesion and structural stability

Evaluate available TCO materials

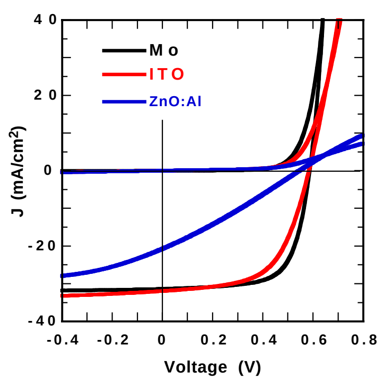
- Calculate equilibrium stability in Se_2 at 400°C
- ZnO - actually ZnO:Al_2O_3(2%)
- ITO - actually In_2O_3:SnO_2(9%)

reaction, at 400°C	ΔG_{rxn} (kcal/mol)
$2ZnO + Se_2 \rightarrow 2ZnSe + O_2$	104
$2Al_2O_3 + 3Se_2 \rightarrow 2Al_2Se_3 + 3O_2$	416
$2In_2O_3 + 3Se_2 \rightarrow 2In_2Se_3 + 3O_2$	172
$SnO_2 + Se_2 \rightarrow SnSe_2 + O_2$	74

Transparent back contact for $Cu(InGa)Se_2$

Deposit $Cu(InGa)Se_2$ on Mo, ITO, and ZnO

- In a single $Cu(InGa)Se_2$ run
- all contacts deposited on standard soda lime glass
- T_{SS} = 400°C
- Ga/(In+Ga) = 0.32, E_g = 1.20eV
- no apparent difference in composition, morphology



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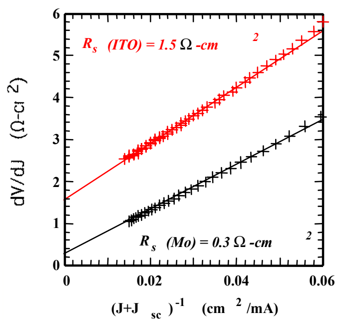
Transparent back contact for Cu(InGa)Se_2

contact	Voc (V)	Jsc (mA/cm^2)	FF (%)	eff (%)	Roc (ž -cm^2)
Mo	0.587	31.4	67.7	12.5	2.0
ITO	0.584	32.0	58.4	10.9	3.7
ZnO	0.544	20.7	27.7	3.1	23

- **ITO/Cu(InGa)Se_2 cell comparable to Mo/Cu(InGa)Se_2 except series resistance**
- **as-deposited**
  - **R_{sheet}(Mo) ≈ 0.2Ω/□**
  - **R_{sheet}(ITO) ≈ 20 Ω/□**



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Future research focus

$CuIn_{1-x}Ga_x(Se_{1-y}S_y)_2$

- **Verify control of chalcogen sources. Calibrate all sources.**
- **Develop process to deposit films with uniform composition. Characterize films, devices.**

$Cd_{1-x}Zn_xTe$

- **Determine effects of post-deposition treatments in halide, oxygen and inert ambient at 300 - 500°C.**
- **Fabricate and characterize devices.**

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High Performance PV
October 18, 2001

National Center for Photovoltaics

NCPV Thin-Film Tandem Research

D.L. Young, T.J. Coutts, T. Gessert, S. Ward, R. Noufi, S. Asher,
K. Emery, D. Levi, H. Moutinho, Y. Yan, P. Sheldon, M. Symko-Davies

High-Performance Photovoltaic Project

National Center for Photovoltaics

➢ The Plan

Goals

Exploration of materials/devices

Tandem cell development ~15%

25% poly. thin-film tandem

Year 1 — Year 3 — Year 5 — Year 10

Milestones

2002: 10%, $1.6 < E_{gap} < 1.8$ eV Cell

2003: Interconnect scheme for monolithic tandem

2004: Refine device design

2005: 15% thin-film tandem

2006: 20% thin-film concentrator sub-module

High-Performance Photovoltaic Project

National Center for Photovoltaics ➢ Perspective

Address at Rice University on the Nation's Space Effort
President John F. Kennedy
Houston, Texas
September 12, 1962

"We set sail on this new sea because there is new knowledge to be gained, and new rights to be won, and they must be won and used for the progress of all people."

"We choose to go to the moon. We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too."

"But if I were to say, my fellow citizens, that we shall send to the moon, 240,000 miles away …a giant rocket more than 300 feet tall,… **made of new metal alloys, some of which have not yet been invented**, capable of standing heat and stresses several times more than have ever been experienced, fitted together with a precision better than the finest watch, carrying all the equipment needed for propulsion, guidance, control, communications, food and survival, on an untried mission, to an unknown celestial body, and then return it safely to earth,… and do all this, and do it right, and do it first before this decade is out--**then we must be bold**."

High-Performance Photovoltaic Project

National Center for Photovoltaics ➢ 2002 tasks

NCPV Thin-Film Tandem Research - 2002 A.O.P.

- Modeling
- Thin film concentrator cells
- Sub-cell interconnect
- Exploration of wide bandgap top cell materials
- New equipment and personnel

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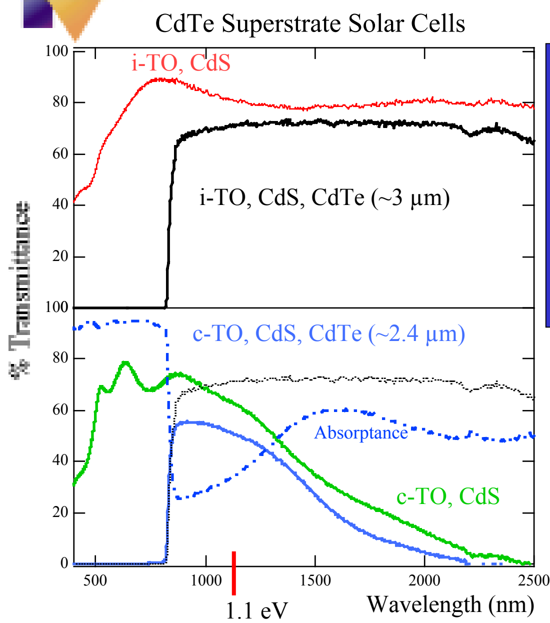
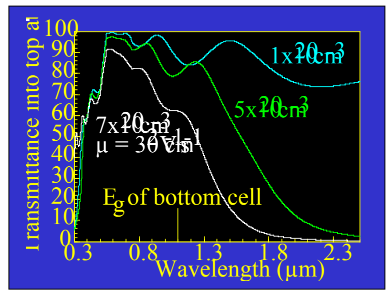
➢ Modeling





- Tandem-specific TO grown by CVD. (X. Li)
- Electronic transport simulation -> AMPS-1D

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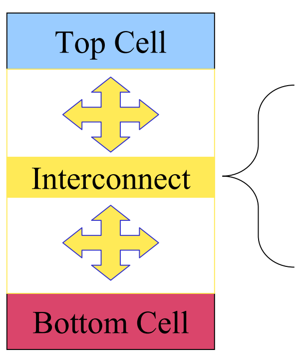

➢ Sub-cell interconnect

- n^{++}/p^{++} defect, tunneling structures
- n^{++}/ p “one-sided shorting junction”
- ZnO, SnO_2, ITO, Cd_2SnO_4
- ZnTe:Cu
- a-Si
- $Cu_{2-x}Se$
- n-$CuInO_2$:Sn / p-$CuInO_2$:Ca
- Other materials w/ E_{gap} > 1.7 eV
- metallic grids

➢ Absorber nucleation, J/V quality, optical quality, thermal limits.

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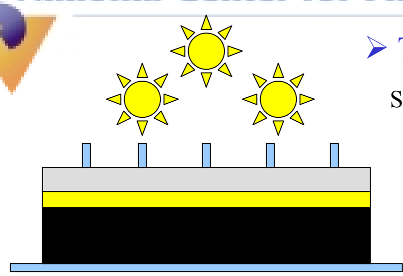
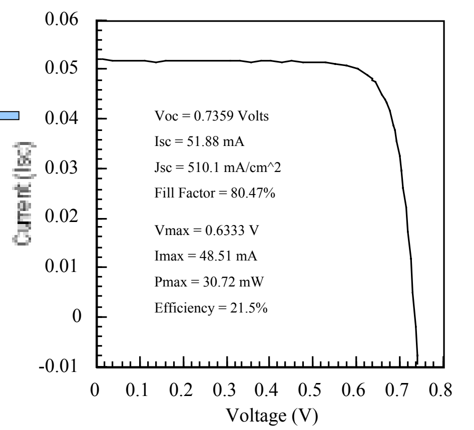
National Center for Photovoltaics

➢ Thin-Film Concentrator Cell-2001

S. Ward *et al*. Progress in Photovoltaics, in press.





- Modified CIGS cell
- 14.05 Suns (direct)
- 21.5%
- 80.5% fill factor
- Voc = 736 mV

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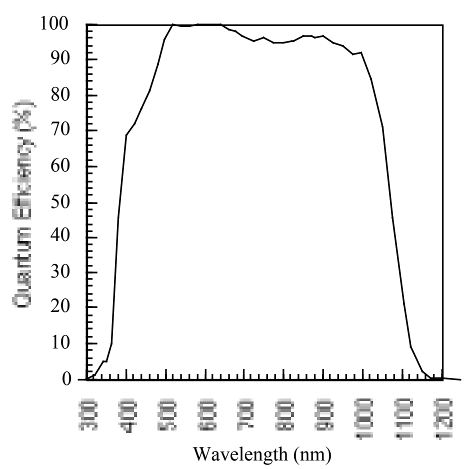
National Center for Photovoltaics

➢ Thin-Film Concentrator Cell-2002

- Thin CdS window/buffer layer (Enhanced blue response)
- Replicate results on a thermally conductive substrate
- Investigate alternative window/buffer layer concepts
- Fabricate on-sun testing devices
- Explore CdTe, superstrate cells



High-Performance Photovoltaic Project

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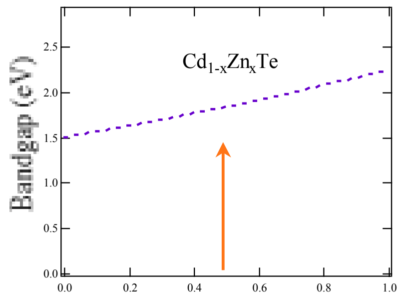
➢ Top Cell

$Cd_{1-x}Zn_xTe$ Top Cell

Top Cell - $Cd_{1-x}Zn_xTe$ (1.7eV)

Bottom Cell? - (1.1 eV)



- CSS deposition of $Cd_{1-x}Zn_xTe$ with x ~ 0.5 (1.7 eV)
- Working with Cerac to fabricate targets
- ZnTe transparent back contact

High-Performance Photovoltaic Project

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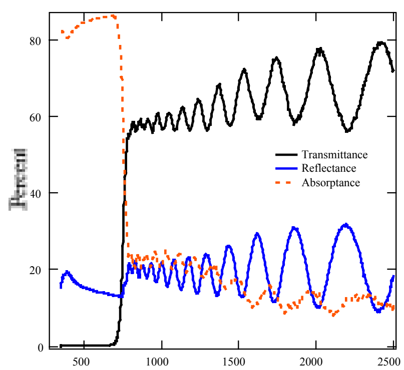
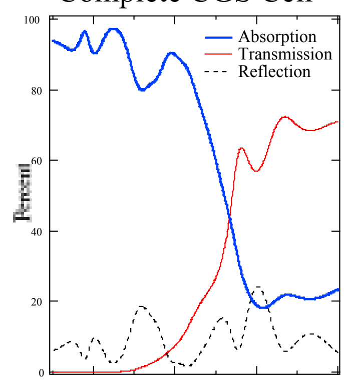
➢ Top Cell

$CuGaSe_2$ Top Cell (1.7 eV)

CGS on Glass



Complete CGS Cell



- Elemental evaporation ("3-stage" process)
- Good sub-bandgap transmission
- Transparent back contact (ITO, SnO_2)

- Can we eliminate CdS window layer?

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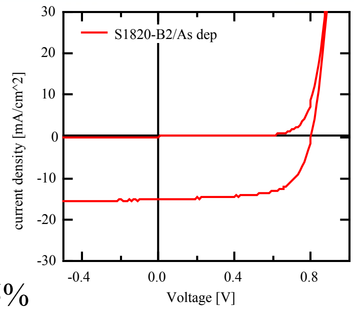
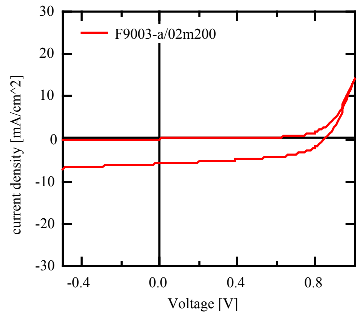
➢ Top Cell

• Can we make a 10% (17%) CGS Cell?

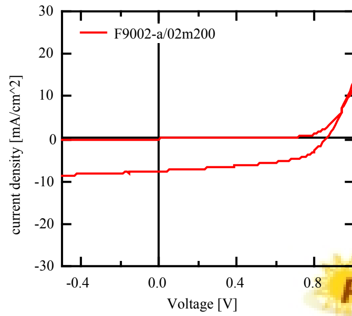


CGS on Mo ~ 8%
V_{oc} = 0.80 V
F.F. = 66.3%

CGS on ITO ~ 2.5%



CGS on TO ~ 3.4%



Voc = 0.86 V
F.F. = 51.8%

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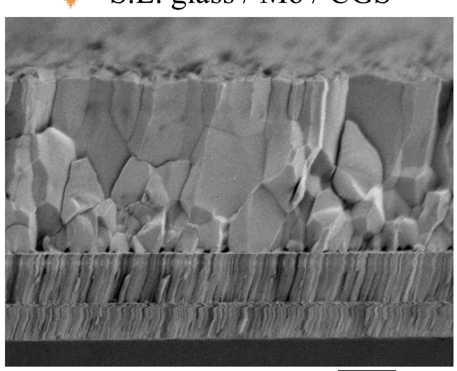
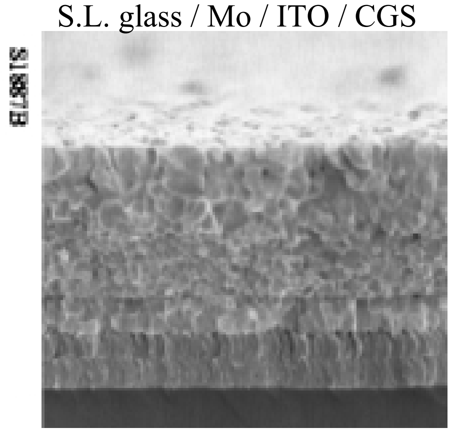
➢ Top Cell

S.L. glass / Mo / CGS



1μm 15000X

S.L. glass / Mo / ITO / CGS



2 μm 15000X

• Nucleation on back contact material
• Diffusion of Na from glass to CGS - SIMS

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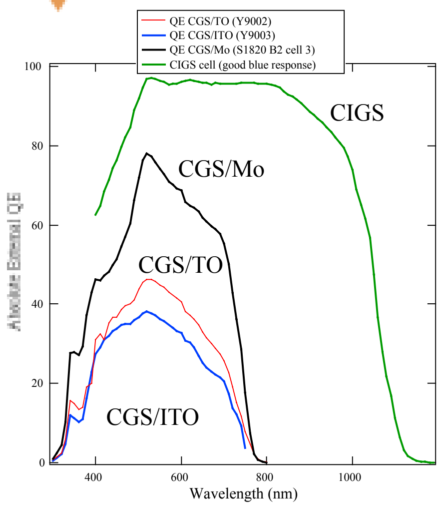
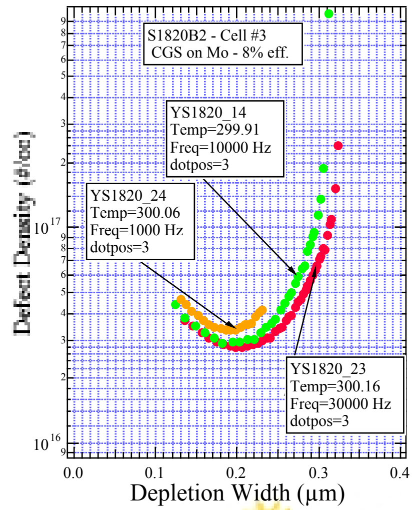
➢ Top Cell

Relative QE Data



Drive-level capacitance



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➢ Equipment and Personnel

- Retool existing Solar-X evaporator
  - 5 sources
  - Active substrate cooling

- Recruit in-house specialist to work on High Performance goals.
  - ~1/3 of NREL work ➡ Future PV

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“And, therefore, as we set sail we ask God's blessing on the most hazardous and dangerous and greatest adventure on which man has ever embarked.”

- J.F. Kennedy 1962

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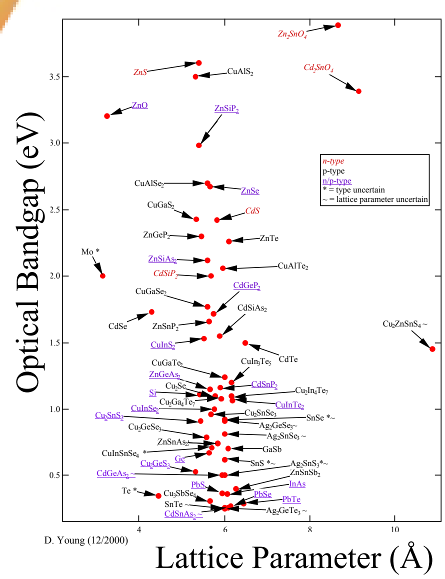

➢ Top Cell Materials

- Literature search based on optical modeling

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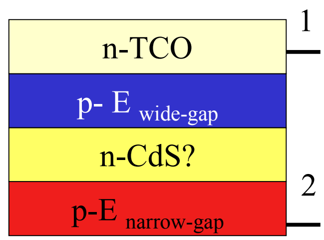
➢ Top Cell

New Materials for Tandem Cell

$ZnSiAs_2$ - 2.12 eV
$CuGaSe_2$ - 1.7
$CuAlTe_2$ - 2.06
ZnTe - 2.12
$ZnSnP_2$ - 1.66
$CuAlSnSe_4$ - 1.90
$ZnGeP_2$ - 2.3
$ZnIn_2Se_4$ - 2.05
$ZnIn_2Te_4$ - 1.87
$CdGeP_2$ - 1.72
$CdSiP_2$ - 2.05
Se (:I, VII) - 1.8



$CuInSe_2$ - 0.95 eV
$CuInSnSe_4$ - 0.71
$CuGaTe_2$ - 1.24
$Cu_2Ga_4Te_7$ - 1.08
$CuInTe_2$ - 1.1
$ZnGeAs_2$ - 1.15
Cu_2GeSe_3 - 0.79 - 0.94
Cu_2SnS_3 - 0.91
Cu_2SnTe_3 - 0.96
GaSb - 0.70
Si - 1.1

High-Performance Photovoltaic Project

High Performance PV Research at U. of Toledo: "Polycrystalline Thin-Film Tandem PV Cells"

- First Solar, LLC, is a major lower-tier subcontractor
- University of Toledo focus:

First Year --

• magnetron sputtering of wide gap II-VI alloys for top cells with emphasis on CdZnTe

• magnetron sputtering of ZnTe:N and ZnO:Al for top cell transparent back contacts and recombination junctions

• (with FS) study of HRT layers for reduced CdS thickness

• (with FS) fabrication of four-terminal stacked device with CIS bottom cell

Second year--

• optimization of CdZnTe or other II-VI with special focus on post-deposition chloride heat treatment

• optimization of recombination junctions between wide-gap II-VI and CIS

• exploratory work on magnetron sputtered HgCdTe for bottom cells with possible fabrication of two-terminal structures with MS and/or VTD top cells

• characterization of materials-- PL, EL, Raman, XRD, Hall, photo-Hall, SEM/EDS

• device characterization including QEs of component cells of two-terminal structures

Absorber Layer, $Cd_{1-x}Zn_xTe$

Top Cell Absorber Layer Band Gap ~ 1.7-1.85 eV

CdTe Band Gap ~ 1.5 eV

ZnTe Band Gap ~ 2.2 eV

Preparation of Cd1-xZnxTe Films: By Magnetron Sputtering

Target: in house target fabrication with mixture & sintered $Cd_{1-x}Zn_xTe$

Challenge: Post deposition treatment

Transparent Recombination Contact

ZnTe:N - - Band Gap ~ 2.2 eV

- Prepared by Reactive Sputtering Technique
- N_2 Composition: 0 - 5% in Ar

Effect of N doping

Structural: orientation changes from (111) to (220)

Morphology: grain size decreases from 130 to 36 nm

Energy Band Gap: No trend, between 2.16 to 2.22 eV

Properties of ZnTe:N Films (3% N_2)

Resistivity: ~ 8 ohm-cm (as deposited)

: ~ 3 ohm-cm (heat treated in air)

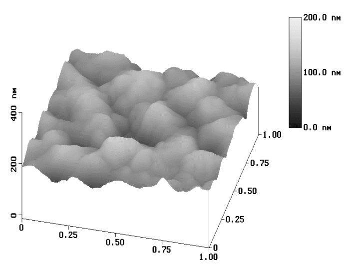
Carrier concentration: ~ $5x10^{18}$ cm^{-3}

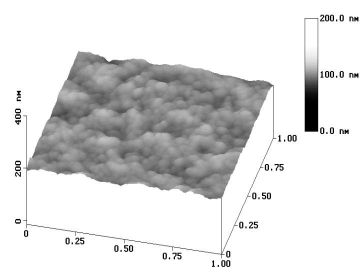
Mobility: ~ 0.3 cm^2/V-s

ZnO:Al Films: By Magnetron Sputtering Technique

Window Layer: Use of High-resistive Tin Oxide to decrease CdS thickness

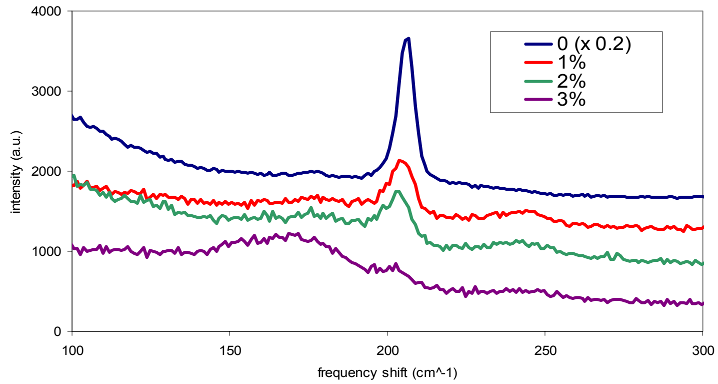
Atomic Force Microscopy of ZnTe Films





AFM images of ZnTe (left) and ZnTe:N (right) films sputtered with 3% N_2/(Ar+N_2) on microscope slides.

Raman Spectra of ZnTe and ZnTe:N films

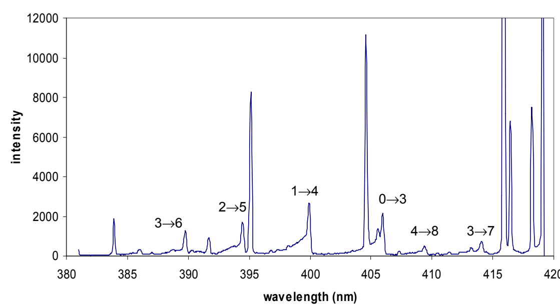


(1% and 3% spectra are offset by 1000 and 500 respectively)

- As doping increases, the LO peak at 203 cm^{-1} decreases in intensity.
- Free carrier screening shifts LO to the TO position at 170 cm^{-1}
- Broad peak for 3% suggests density-of-states scattering appropriate for a partial amorphous film.

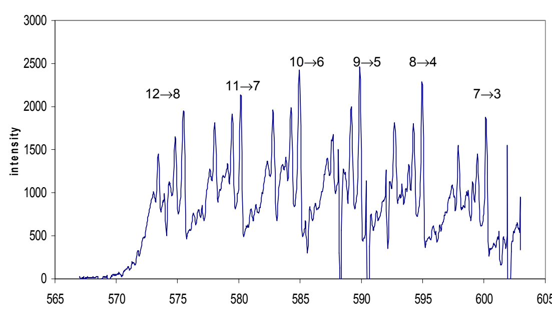
OES spectra of N_2 near target

Second positive band ($C^3\Pi_u$ – $B^3\Pi_g$)

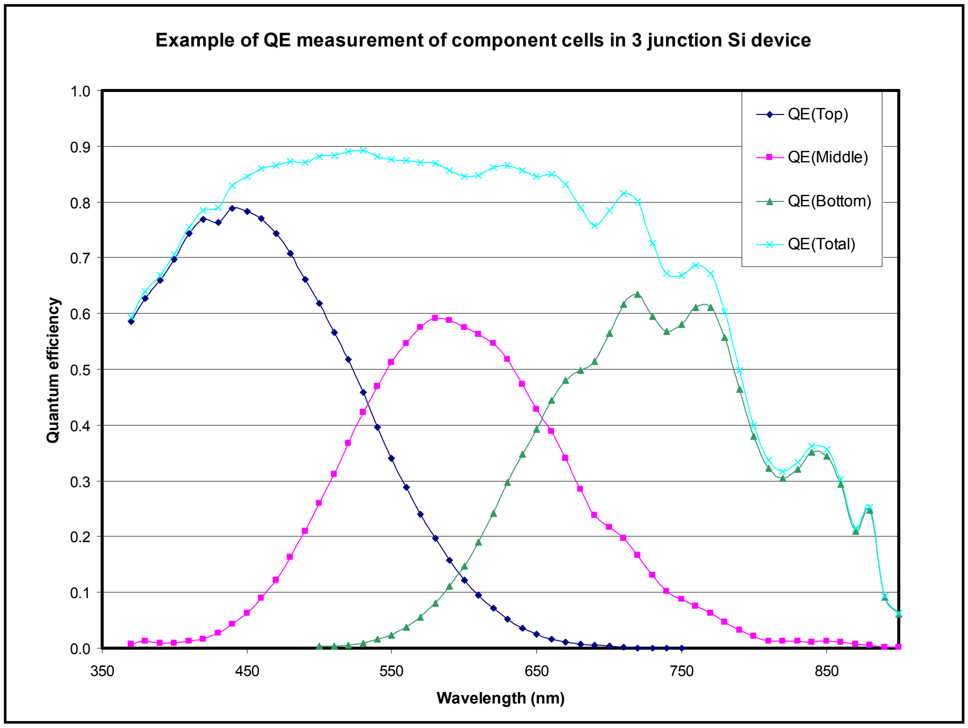


First positive band

($B^3\Pi_g$ – $A^3\Sigma^+_u$)



[sputter power 40W, press = 18mT. Ar lines have been subtracted.]



Example of QE measurement of component cells in 3 junction Si device
Quantum efficiency
Wavelength (nm)
QE(Top)
QE(Middle)
QE(Bottom)
QE(Total)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
350
450
550
650
750
850

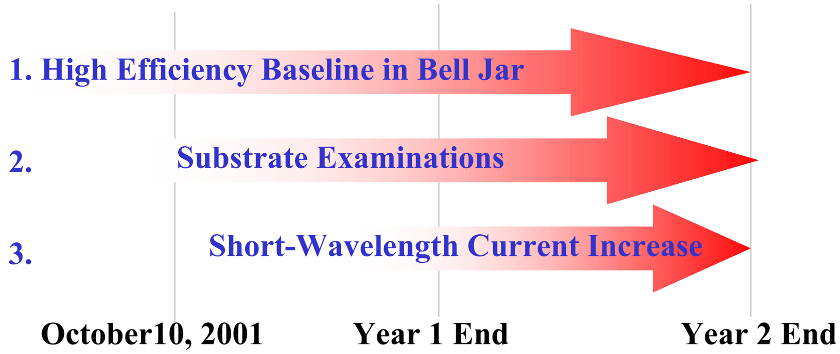
Plans for Global Solar Energy's High-Performance Program

Prime Contractor: Global Solar Energy
Lower-Tier Subcontractor: ITN Energy Systems
Track: Thin-Film Concentrator

Phase I: How do we move thin film CIGS devices on metal foil toward 20% efficiency?

1. **Eliminate efficiency differences between devices on steel and on glass.**
2. **Increase short-wavelength current collection.**

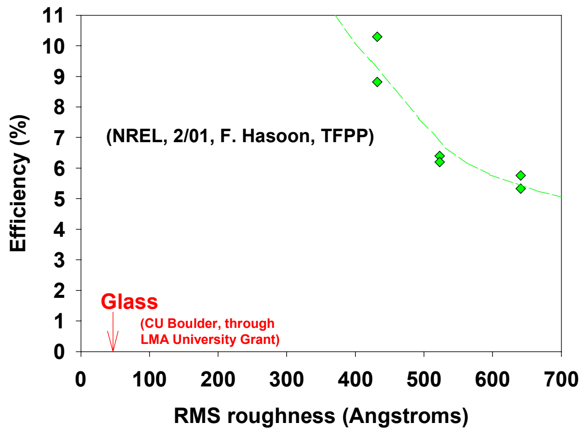
Scheduling:



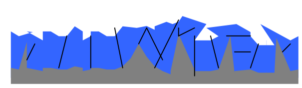
Substrate Examinations: Eliminate efficiency differences between best devices on steel and best devices on glass.

1. Substrate roughness
2. Harmful impurity diffusion, with and without barriers
3. Modified NaF incorporation
4. Substrate Temperature

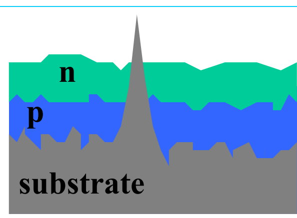
Substrate Roughness:



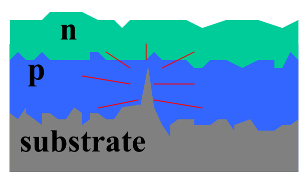
Mechanism:



Altered Grain Growth?



Shunt Paths?



Source of Impurities?

Activities:

- AFM
- Electropolishing
- IV Characterization
- Device Fabrication

Experiments:

- η vs. roughness. Can we approach smoothness of glass with electropolishing?
- Is roughness equally harmful for foils without harmful impurities? (Mo, Ti)
- How much does Mo mask the bare substrate roughness?
- Does NaF precursor morphology affect growth surface? Is it better deposited after In_2Se_3 growth?

Substrates, Harmful Impurity Diffusion

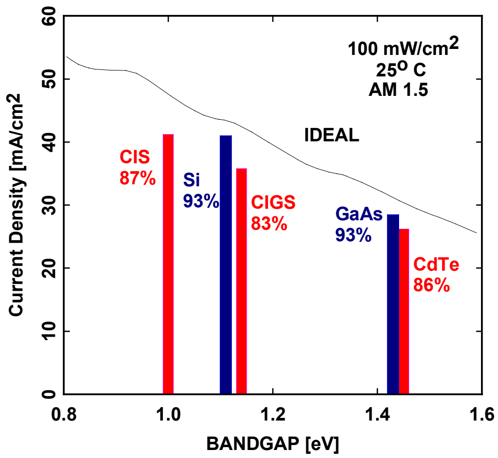
Activities:

- Device Fabrication
- Diffusion Barrier Deposition
- IV Characterization
- SIMS

Experiments:

- Device performance and Fe, Cr, C concentrations vs. Mo thickness
- Device performance and Fe, Cr, C concentrations vs. barrier (such as Cr) thickness and properties
- Do roughness studies on Mo and Ti foils help quantify effect of impurities?

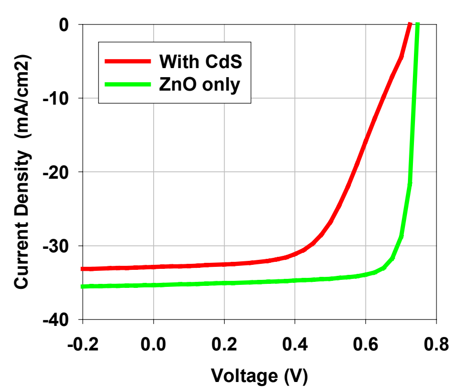
2. Why Focus On Short-Wavelength Current Increase?



- CIGS has realized only 83% of its potential current collection, compared to over 90-95% for voltage and ff.
- NREL 15% Cd-free device collects 1.7 mA/cm^2 more current below CdS bandgap than record 18.8% device.
- (Graph not updated to include recent CdTe record.)

Hypothesized functions of CdS:

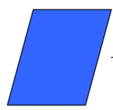
- Diffusion of Cd into CIGS
- Protection from PVD
- Creation of lattice-matched interface
- Mitigation of localized shunts
- CIGS surface reduction in bath



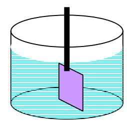
ADEPT modeling: CdS *NOT* necessary for successful band structure.

Examine each role, determine importance and how might be replaced with higher-transmission option:

- Mitigate localized shunts
- Protect from PVD



CIGS



Partial electrolyte treatment

ρ, P—	ρ —, P
ρ , P	ρ , P
ρ , P+	ρ + , P
RF vs. PDC?	

i-ZnO matrix

TCO, characterization

- Diffusion of Cd into CIGS

Activities:

- Partial Electrolyte Treatment
- Device Fabrication
- IV Characterization
- Comparitive SIMS?

Variables:

- Immersion time
- Bath temperature
- Applied voltage
- $CdSO_4$ concentration
- NH_4OH concentration
- CIGS near-surface composition

♦ Creation of lattice-matched interface

♦ CIGS surface reduction in bath

Deposit very thin CdS layers?

– Slow down bath with lower thiourea concentration or lower temperature.

– Vary thickness by varying sample immersion time.

Valid examination *if*

– Oxidation creates active defects at CIGS/CdS interface, but not at CdS/ZnO interface.

– Lattice matching-related defects between CdS and ZnO are less active than those between CIGS and ZnO.

– Or, junction is entirely in CIGS.

Otherwise, defects are still very close to junction.

SUMMARY

Program objectives are to:

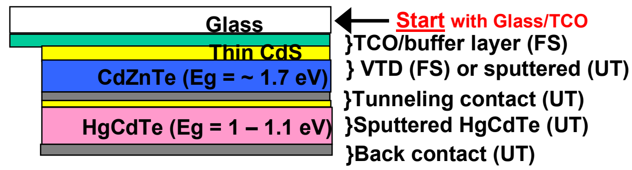
1. Determine the important variables in the efficiency differences between the best devices on glass and the best devices on steel.

2. Improve short-wavelength current collection by determining the important functions of the CdS and replacing it.

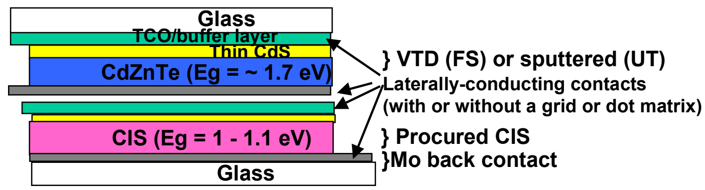
3. Demonstrate at least 16% efficient CIGS devices on metal foil that demonstrate improved blue light collection and insignificant efficiency degradation between glass and steel.

Tandem device structures under investigation

- **Superstrate CdS/CdZnTe, $Hg_xCd_{1-x}Te$ (2 terminal):**



- **Superstrate CdS/CdZnTe in 4-terminal device (with CIS bottom cell):**



- **Substrate CdS/CdZnTe grown on CIS or HgCdTe bottom cell (2 terminal) (UT)**

Task 1: Make and supply substrates to UT

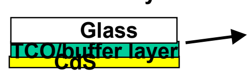
- **Supply:**

To support UT development of:

- glass/TCO/HRT:

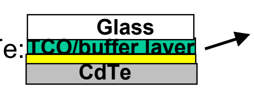
- •CdS/CdTe sputtered top cell

- glass/TCO/HRT/CdS:



- •CdTe sputtering

- glass/TCO/HRT/CdS/CdTe:



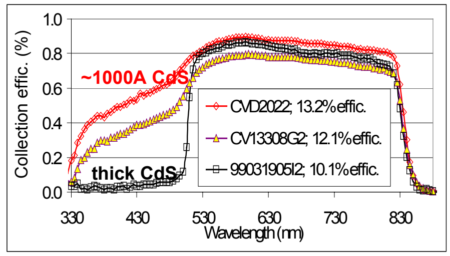
- •Tunneling contact
- •Sputtered bottom cell
- •Mechanical-stack

- Comments:
  - UT has found that some FS $CdCl_2$-treated glass/TCO/HRT/CdS/CdTe substrates are more suited than others to an no-etch back contact process. We have worked to identify substrates that will perform well with their process.

Task 2: Investigate tailoring buffer/thin CdS

- Buffer layer and thin CdS with optimized properties are important to high efficiency with single junction CdS/CdTe cells:

  "" even more important in tandem cells.



- Capabilities to investigate buffer layers include an atmospheric-pressure chemical vapor deposition (APCVD) system with 60cm-web and 1 plate/min throughput

APCVD system for buffer layer deposition

10/18/01, High Performance PV Kickoff Meeting, First Solar, LLC

Task 3: Explore feasibility of CdZnTe by VTD

- Task: Explore the feasibility of depositing CdZnTe with controlled levels of Zn with research-sized Vapor Transport Deposition (VTD) system; characterize films by spectrophotometry, EDS and SEM.

Small area VTD system (10 cm x 10 cm samples):

10/18/01, High Performance PV Kickoff Meeting, First Solar, LLC

Other year 1 tasks for First Solar

- Interconnect and laminate top cells with CI(G)S bottom cells for mechanically stacked cells
- Light-soak and characterize single and dual-junction cells developed as part of this effort

10/18/01, High Performance PV Kickoff Meeting, First Solar, LLC

Year 2 tasks for First Solar

- Make and supply samples to UT to support magnetron-sputtered top-cell absorber layer, top-cell-contact, bottom-cell, and mechanical-stacked cell development efforts:
  - glass/TCO/HRT; glass/TCO/HRT/CdS; glass/TCO/HRT/CdS/CdTe
- Optimize HRT/thin-CdS layers for use in top cells with CdZnTe
- Deposit by VTD CdZnTe with controlled levels of Zn for use with two-terminal and four-terminal tandem cells; characterize films by spectrophotometry, EDS and SEM.
- Interconnect and laminate top cells with CI(G)S bottom cells for mechanically stacked cells
- Light-soak and characterize single and dual-junction cells developed as part of this effort

10/18/01, High Performance PV Kickoff Meeting, First Solar, LLC

Some other relevant facilities

- **Processing at Technology Center:**
  - Module scale back-contact deposition and processing equipment
  - Sputter-deposition and e-beam evaporation systems
  - Ventilation hoods and wet-chemistry for pre- or post-contact treatments
  - 2 ovens for heat treatments
  - Small-area (100 cm^2) APCVD system for specialty buffer layers
  - Small-sample encapsulation
- **Finishing line at factory** for 60 cm x 120 cm modules (1 plate/min designed capacity)
- **Accelerated-life testing (ALT) systems:**
  - Light-soak stations for 400 10cm x 10cm samples and 26 modules
  - 3 ovens for dark stress ALT (with N_2 purge and external bias stress options)
- **Characterization systems:**
  - Xenon-lamp solar simulator (measures up to 18 cells at once; tracked in database)
  - CV/CF system for carrier-concentration and trap characterization
  - Varian Cary 500 spectrophotometer with integrating sphere
  - SEM with EDS capability
  - Solar cell spectral response measurement system (monochrometer-based with Xenon lamp source)
  - X-Y mapping systems with 4-pt resistance, CdS and CdTe thickness by transmission, SPV, and PL of CdTe.

Development of a II-VI-Based High Performance, High Band Gap Device for Thin-Film Tandem Solar Cells

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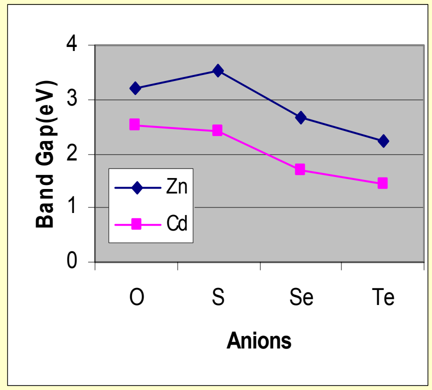
SUPPORTED BY THE NATIONAL RENEWABLE ENERGY LABORATORY

OUTLINE

- **Tandem solar cells**
  - Why? to reach 25% efficiencies
  - How?
    - Using a 16-18% high band gap top cells
    - Top Eg=1.7 eV, bottom Eg=1.0 eV (CIGS)
  - II-VI compounds can be used for top cell
- **Device structure**
- **AMPS Modeling**
  - Bottom cell vs. thickness of top absorber
    - Light J-V
    - SR
    - Jsc and η
  - Top Cell performance vs. thickness
  - Tandem Cells
- **Approach**

Background

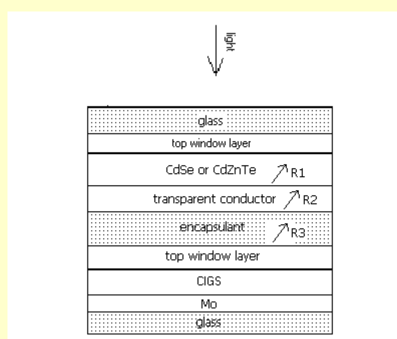
- The band gap combination 1.7/1.0 eV is near-ideal for a 2-terminal tandem
- CIGS with a band gap of 1.0 eV and an efficiency of 15% is the clear choice for the bottom cell
- To reach 25% the top cell will have to be in the 16-18% range since it will contribute about 2/3rds of the output
- As seen in figure 1, II-VI compounds have the requisite band gaps
- $Cd_xZn_{1-x}Te$(CZT) covers the range 1.45-2.2 Ev and can capitalize on successes with CdTe technology
- CdSe has a band gap near the ideal of 1.7 eV and is a binary



Department of Electrical Engineering, Center for Clean Energy and Vehicles,
Presented at the 1st High Performance PV Meeting, NREL, October 18, 2001.

Device Structure

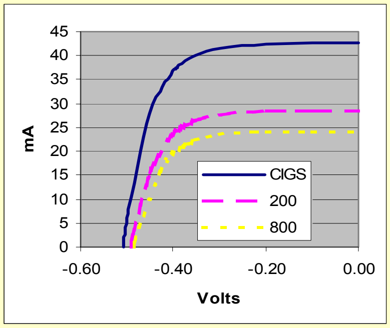
- A 4-terminal structure is proposed as shown in figure 2.
- Top Cell: II-VI; Bottom Cell: CIGS
- Preliminary calculations indicate that reflection losses to the bottom cell can be kept to 10%
- Key issue: Transparent Contact for top cell.
- Window Layers – several options
- Substrates: Glass!



Department of Electrical Engineering, Center for Clean Energy and Vehicles,
Presented at the 1st High Performance PV Meeting, NREL, October 18, 2001.

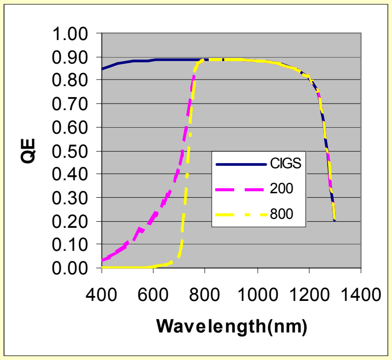
AMPS Simulation – Bottom Cell vs. Thickness of Top Absorber

- Achieved parameters for a 14.7% 1.0 eV CIGS cell are used for the bottom cell (J_{sc} = 42.6 mA/cm^2, V_{oc} = 508 mV, FF = 0.68,)
- The thickness of the top 1.7 eV cell is varied from 200 to 800 nm.



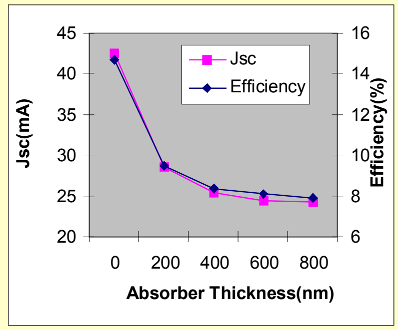
AMPS Simulation – Bottom Cell QE vs. Thickness of Top Absorber

- There is a large drop in Jsc for 200 nm, but the drop slows significantly as the top cell thickness is increased to 800 nm



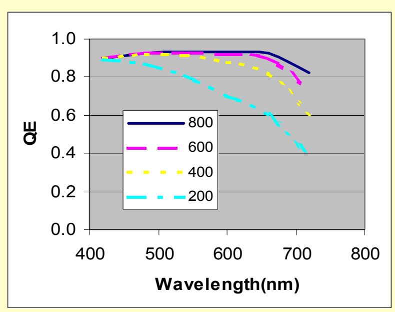
AMPS Simulation – Bottom Cell Performance

- J_{sc} asymptotes toward 25 mA/cm^2
- Efficiency of the bottom cell is in the range of 8-9% for the 400-800 nm thickness range

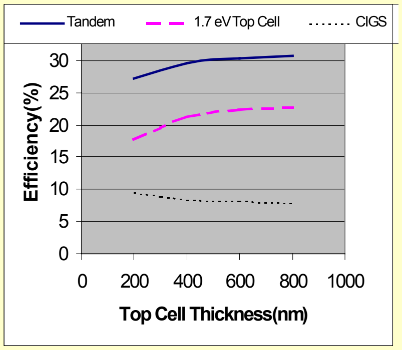


AMPS Simulation – Top Cell QE

- Not much loss in the top cell occurs when its thickness is reduced to the 400-600 nm range



AMPS Simulation – Tandem Performance (ideal)



- Using idealized values for a top cell of Eg 1.7 eV, the efficiency is in the low 20% range for 400-800 nm thickness
- This results in a tandem efficiency of 30+%

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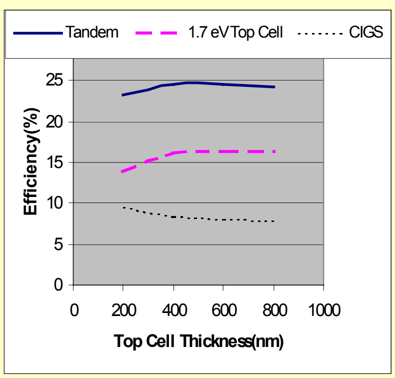
AMPS Simulation – Tandem Performance (real!)



- Using typical values of parameters (CdTe) yields a top cell efficiency in the desired range above 16% and a tandem efficiency of 25%.

Department of Electrical Engineering, Center for Clean Energy and Vehicles,
Presented at the 1st High Performance PV Meeting, NREL, October 18, 2001.

Deposition Technology – Current Status

- **Deposition Technology:**
  - New deposition system with co-evaporation capabilities will be constructed for this project
  - Close spaced sublimation (available)
  - RF-sputtering
- **Challenges: develop ABSORBER and its TRANSPARENT CONTACT**
- **Project started on 09/01:**
  - Begun deposition of II-VI films using existing deposition capabilities.

Department of Electrical Engineering, Center for Clean Energy and Vehicles,
Presented at the 1st High Performance PV Meeting, NREL, October 18, 2001.

NREL High Performance PV Program

Identification of Critical Paths in the Manufacture of Low-Cost High-Efficiency CGS/CIS Two-Junction Tandem Cells

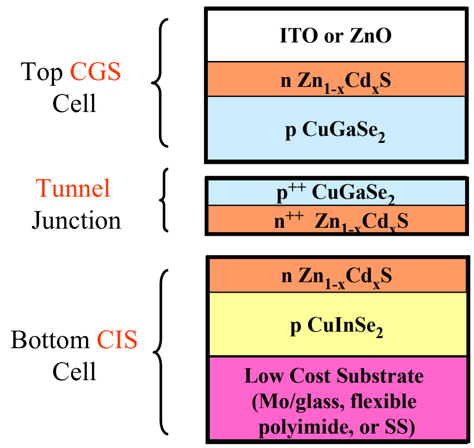
by
Oscar D. Crisalle
University of Florida
Gainesville, FL

Program Kick-Off Meeting, Golden, CO, October 18, 2001

Principal Investigators

- Prof. Oscar D. Crisalle
  - Chemical Engineering Department
  - Instrumentation, process modeling and control
- Prof. Sheng S. Li
  - Electrical & Computer Engineering Department
  - Device design, characterization, & optimization
- Prof. Tim J. Anderson
  - Chemical Engineering Department
  - Materials growth, characterization, & optimization

Proposed Tandem Cell Structure



$CuGaSe_2$ $E_g = 1.68$ eV, $a_o = 5.61$ Å

CdS $E_g = 2.4$ eV, $a_o = 5.82$ Å

ZnS $E_g = 3.7$ eV, $a_o = 5.42$ Å

$CuInSe_2$ $E_g = 1.04$ eV, $a_o = 5.78$ Å

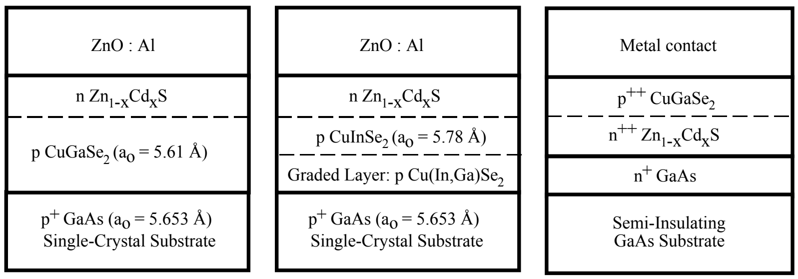
IDEAL BG ENERGIES
Top: $E_g = 1.8$ eV
Bottom: $E_g = 1.0$ eV

Critical Issues

- Tunnel junction:
  - Fabrication of a transparent, low resistance, lattice-matched, and heavily-doped junction.
  - Low temperature deposition process
- Top cell (CGS)
  - Improved conversion efficiency
  - Low temperature deposition process

Approach

- Study each component separately during Phase I
- Reduce complexity by growing single-crystal films on GaAs (use low-cost substrates in Phase II)

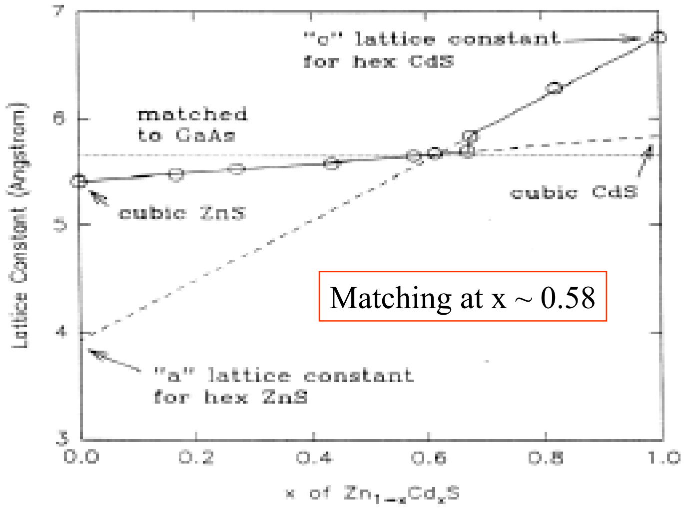


(a) Top-Cell Structure (CGS) **(b) Bottom- Cell Structure (CIS)** **(c) Tunnel-Junction Structure**

Project Goals

- Identify the critical manufacturing and materials issues for achieving a 25% conversion efficiency CGS/CIS two-junction tandem solar cell.
- Fabricate a bottom CIS cell with a conversion efficiency in the 13% - 15 % range.
- Fabricate a top CGS cell with a conversion efficiency in the 10% - 13 % range.
- Fabricate a low resistance and high quality tunnel junction interconnecting the top and bottom cells.

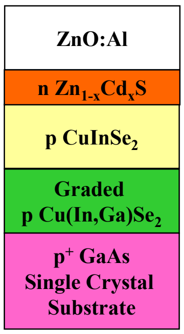
$Zn_{1-x}Cd_xS$ Lattice



Migration-Enhanced Epitaxial Growth

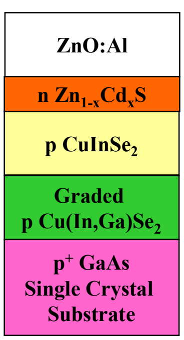
MEE
Reactor

Bottom CIS Cell - Activities Proposed



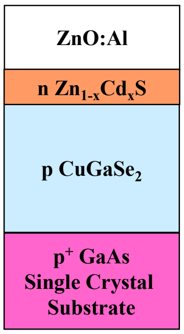
- Take advantage of standard processing technology
- Grow and characterize single-crystal epitaxial CIS by Migration Enhanced Epitaxy (MEE)
- Single-crystal n^+ GaAs substrates plus graded p $Cu(In,Ga)Se_2$ (or p $In_xGa_{1-x}As$) to reduce the dislocation density and grade the band gap energy
- Grow and characterize $Zn_{1-x}Cd_xS$) layer
- Deposit ZnO:Al layer via sputtering.

… Bottom CIS Cell Activities Proposed



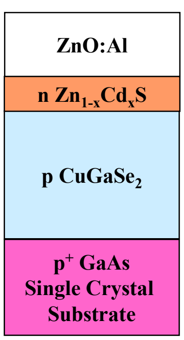
- Dark- and photo- current-voltage (I-V) and capacitance-voltage (C-V) characteristics and spectral response measurements to determine the quantum efficiency.
- Develop an optimal device model for the bottom CIS cell and identify the physical parameters and optimal thickness of each layer using AMPS-ID device simulation program.

Top CGS Cell - Activities Proposed



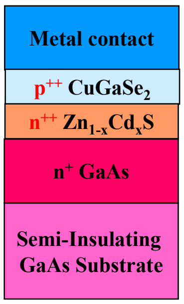
- Grow single-crystal and epitaxial CGS on single crystal substrates by MEE and characterize the CGS absorber layers.
- Investigate an electrodeposition process for CGS as (low temperature process and low cost alternative)
- Optimize the electronic properties of the CGS absorber layer (net hole concentration ~ 10^{16} cm^{-3}, mobility, and lifetime).
- Seek to increase the conversion efficiency (consider the addition of S).

… Top CGS Cell - Activities Proposed



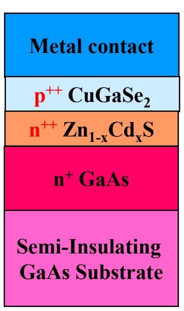
- Investigate temperature, composition and other factors affecting the deposition of the $Zn_{1-x}Cd_xS$ buffer layer
  - Consider CBD and MOCVD processes
- Perform the dark- and photo- I-V characteristics and spectral response measurement of the top CGS cell.
- Develop optimal device model for the top CGS cell and identify the physical parameters & optimal thickness of each layer using AMPS-ID

Tunnel Junction - Activities Proposed



- **Construct a prototype tunnel junction diode**
  - **Determine if CGS can be doped p-type in the 10^{18} cm^{-3} range**
  - **Investigate venues for n^{++} $Zn_{1-x}Cd_xS$ layer deposition**
  - **Explore alternatives for n^{++} doping of the $Zn_{1-x}Cd_xS$ layer**
    - **Utilize intrinsic defects in CBD processing**
    - **Utilize extrinsic dopants (group III (Ga or In) or halide atoms (Cl, Br, or I)).**

… Tunnel Junction - Activities Proposed



- **Characterize the effect of processing via I-V characteristics and the peak current density under different annealing temperatures and duration**
- **Characterize the n^{++} $Zn_{1-x}Cd_xS$ layer by XRD, XPS, SEM, and Hall and transmission measurements**
- **Develop a tunnel junction diode model and identify the physical parameters and optimal thickness of the tunnel junction layer using AMPS-ID.**

Milestones- Phase I Y1

- Produce epitaxial CIS and CGS on lattice-matched substrates.
- Characterize electrical and optical properties of the tunnel junction; determine the optimal thickness/doping level for low optical & electrical losses.
- Develop device model for each component of tandem cell using AMPS-1D device simulation program and predict single-junction cell performance.
- Develop and evaluate a one-step electrodeposition method for growing CGS films.

Milestones- Phase I Y2

- Identify growth parameters for a 10% - 13% efficiency CGS cell
- Identify growth parameters for a 13% - 15% efficiency CIS cell
- Identify growth parameters for a low resistance tunnel junction.
- Develop a CGS/CIS two-junction tandem solar cell model by AMPS-1D and identify an optimized tandem cell structure with a 25 % efficiency.
- Develop and evaluate a two-step electrodeposition method for growing CGS films.

$CuInSe_2$ as a Component in High Efficiency Concentrator Photovoltaics

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arockett@uiuc.edu 217-333-0417

Epitaxial $CuInSe_2$ for Ultrahigh Performance Solar Cells

Multijunction solar cells have achieved very high performances with junctions in excess of 1 eV. Ultimate performances can only be achieved with a 1.0 eV cell.

$CuInSe_2$ is an excellent candidate for this application:

- 1.0 eV energy gap
- Has acheived very high-performance single junctions
- Epitaxial growth has been demonstrated on various surfaces.

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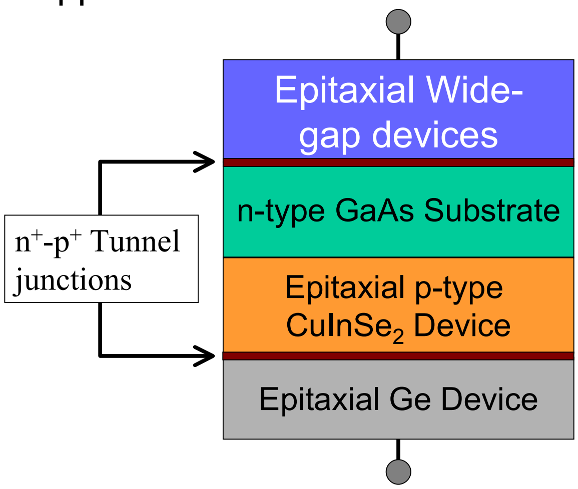
Plan for High Performance Devices

Approach #1: Growth on a GaAs substrate.



Step 1: Grow high-performance wide-gap devices on the GaAs

Step 2: Grow CIS device on the back surface of the GaAs

Step 3: Grow Ge device on the CIS.

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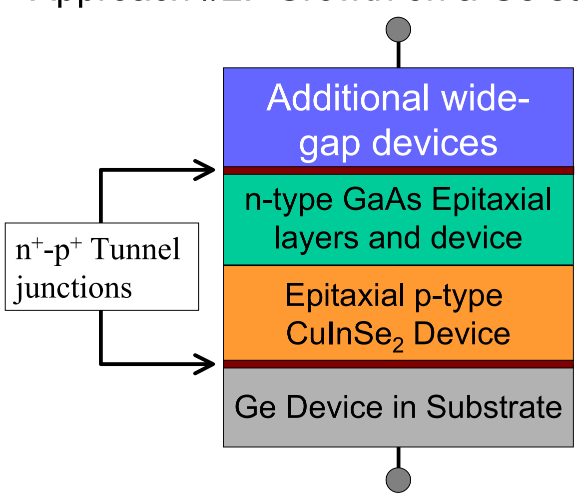
Plan for High Performance Devices

Approach #2: Growth on a Ge substrate.



Step 1: CIS device on a Ge Substrate

Step 2: Grow high-performance devices on the CIS.

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Plan for High Performance Devices

Approach #1: Growth on a GaAs substrate:

Advantages:
- Can begin with a known high performance device
- CIS can be grown on relatively lower quality back surface of the wafer.
- Segregation of impurities from the $CuInSe_2$ into the Ge can probably be stopped with barriers.
- Ge growth requires a relatively low temperature.

Disadvantages:
- Requires a process that the high-performance devices can withstand.
- Defects are likely in the Ge device.

Plan for High Performance Devices

Approach #2: Growth on a Ge substrate:

Advantages:
- Indirect Ge requires a thick layer. Substrate is ideal for this.
- All growth on the same side of the substrate.

Disadvantages:
- Potential for detrimental segregation of material from $CuInSe_2$ into the GaAs can be disastrous.
- Difficult to grow extremely high-performance GaAs on $CuInSe_2$. May lead to poor high gap device junctions.

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Experimental Plan

Determine the performance that can be achieved in CIS junctions

on n^+ GaAs:

- Establish the quality of solar cells that can be produced from epitaxial CIS layers using a p-CIS n-GaAs heterojunction for current collection.

on p^+ and n^+-Ge:

- Establish conditions for epitaxy on Ge.
- Produce solar cells in collaboration with NREL and IEC on these layers.
- Send completed layers to NREL as substrates for high-performance device growth.

Progress to date:

n^+ GaAs Substrates

- Substrates obtained with various orientations
- Epitaxial layers grown
- Preliminary results show diode-like behavior.

p^+ and n^+-Ge Substrates:

- Substrates on order.

Additional ultrahigh vacuum deposition system is being put into order for CIS growth to provide cleaner films and larger substrates (for compatibility with NREL growth systems).

Issues:

n^+ GaAs Substrates

- Growth of Ga-free CIS for 1 eV gap. Ga diffusion from the GaAs substrate could be a problem.
- Deposition conditions exist to minimize diffusion.
- Diffusion within the depletion width of the junction could be a positive effect.
- Need to avoid Cu diffusion into the GaAs.
- Choice of substrate orientation (for junction properties and epitaxial temperature).
- CIS-GaAs heterojunction performance as a solar cell.

p^+ and n^+-Ge Substrates:

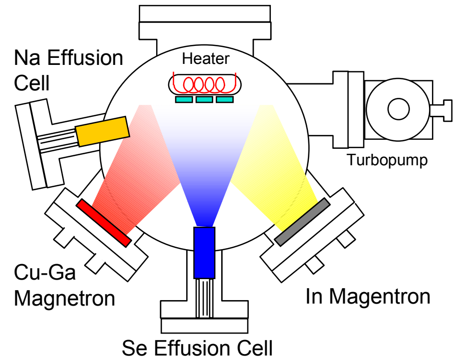
- Past efforts have shown problems with epitaxy on Ge. Extensive work was never performed to determine opportunities.
- And similar issues as above.

Our "Beyond the Horizons" program should also contribute to the Thin Film HiPer program...

Experimental

Film Growth:
T_S = 540 - 725 °C.
Rate ~ 1µm/hr.

Cu-Ga target for Ga-containing alloys



Pure Cu target:

Ga diffuses out of the substrate.

Diffusion rate varies with composition.

Classic Kirkendal voids form at the CIS/GaAs interface.

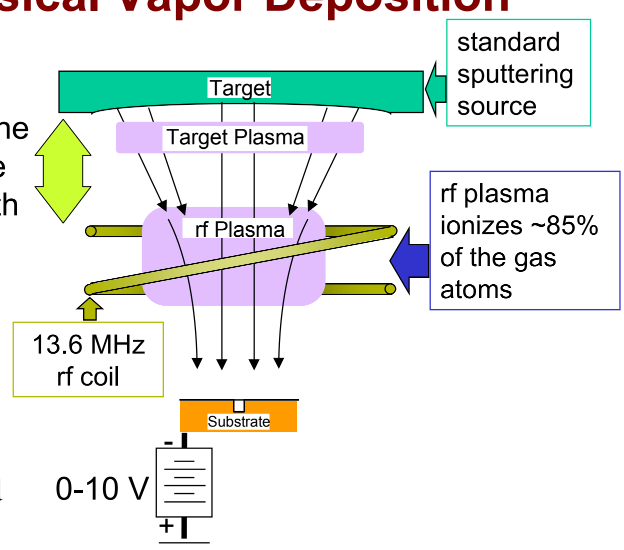
Cu diffusion into the GaAs prevents conduction in the substrate.

Best epitaxy on (111). Rough surfaces on (110).

T_s = 540 ° C (220); 640 ° C (100); and 700 ° C (112)

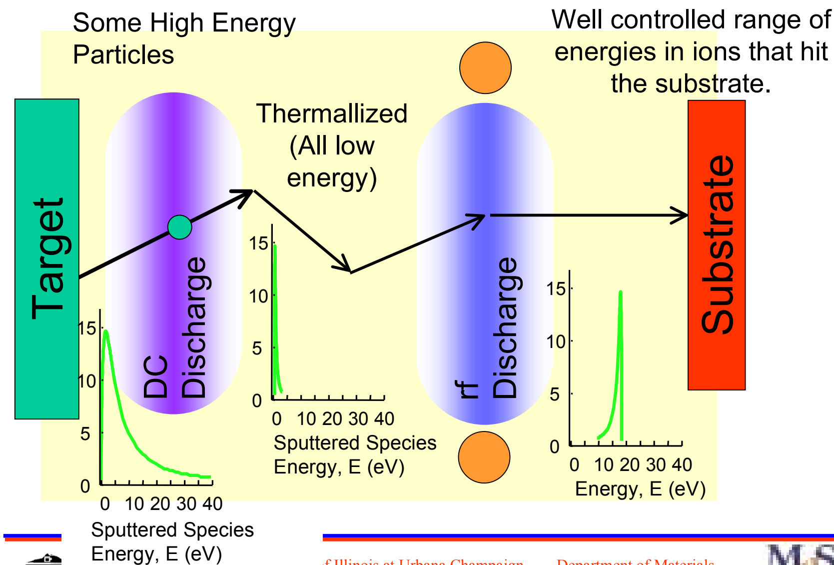
Ionized Physical Vapor Deposition

At least one mean-free path length



Developed at IBM by S. Rossnagle and colleagues.

Ionized Physical Vapor Deposition



Ionized Physical Vapor Deposition

Advantages:

- Simple add-on to existing deposition environments
- Most atoms hit the surface with moderate kinetic energy
- Energy can be controlled to be below the damage threshold but well above the energy needed for surface diffusion and cluster disruption.
- By control of the atom impact energy we can make atoms go where they normally would rather not go without forcing them into defect sites.
- Supply of energy to the growth surface can replace the energy normally supplied by heating.

Experimental Plan

Modify existing deposition systems for ionized physical vapor deposition:

- Existing growth conditions can be used and normal growth continued to show deposition condition stability.
- Add rf coil in front of the substrate in both the existing and the new ultrahigh vacuum deposition systems.
- After establishment of growth conditions, turn on the rf power and show the changes which can be achieved in deposition conditions.
- Produce solar cells from resulting materials for comparison with existing results.

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Current Status

- Contract in place.
- New graduate student hired
- Training in progress
- Parts being assembled for new ultrahigh vacuum deposition system to increase materials production capability

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High-Performance PV Kickoff Meeting (NREL, Denver, 18 Oct 2001)

InGaP/GaAs-on-Ceramic Thin-Film Monolithically Interconnected, Large-Area, Tandem Solar Cell Array

Phase I:

"Development of Low-Cost Substrates and Deposition Processes For High-Performance GaAs-Based Thin-Film Solar Cells"

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website: www.astropower.com

Broad Objective

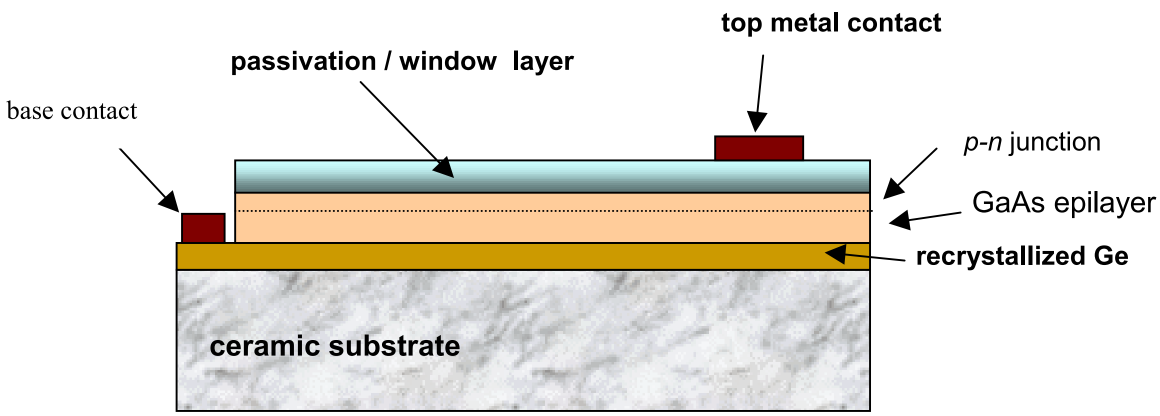
To transfer space solar cell technology that currently yields record-efficiency solar cell performance to a low-cost structure for terrestrial applications

Basic Approach

- replace the expensive single-crystal Ge (or GaAs) substrate wafer with a cheaper alternative
- develop low-cost, high-throughput expitaxy / deposition processes in place of MOCVD
- achieve high efficiencies in GaAs/InGaP solar cells based on thin-films of large-grain (> 1mm) polycrystalline GaAs (and Ge)

Short-Term Goals

- recrystallize Ge films on alumina ceramic substrates to yield highly-oriented, smooth, low-defect layers with grain sizes >> 1 mm
- characterize Ge films electrically and structurally
- use Ge-on-ceramic structures as substrates for GaAs epitaxy. Ge functions as a "seeding layer" for epitaxial growth of GaAs



Criteria for High-Efficiency GaAs-Based Solar Cells

- Close thermal expansion match between substrate / GaAs
- Grain Size > 1 mm
- Close (< 1%) Lattice Matching of Epilayers
- Suppress Silicon and Germanium Autodoping (from Substrate)
- Defect Densities (< 10^5 cm^{-2})
- Suppress antiphase domains (GaAs/Si or GaAs/Ge)
- Front surface passivation or wide-bandgap window layer
- Back surface field or wide-bandgap cladding layers
- Possibly include light trapping (back reflector or front texturing)

New Features

- 1-micron thick undoped "space-charge" layer to reduce tunneling currents [Research Triangle Inst.]
- post-growth grain boundary passivation (plasma H^+ treatments, sulfur or selenium treatments [Milnes et al.], Zn diffusion in grain boundaries)
- all-top contact design for monolithic interconnection (exploiting electrically insulating ceramic substrate)
- buried conducting layer (heavily-doped Ge)

Emitters/Front Surface Passivation

- AlGaAs wide-bandgap "window" layer (LPE or MOCVD) [Hovel]
- InGaP emitter or window (LPE, MOCVD, CVD, CSVT)
- Thin (<100 Å) homojunction [Fan]
- ZnSe emitter or window [Bliske]
- GaAsP emitter or window [Barnett and Parekh]
- Phosphorus "exchange" reaction P + GaAs → GaAsP
- Aluminum "exchange" reaction Al + GaAs → AlGaAs
- Anodic oxidation, SiNx CVD
- Chemical surface treatments (Se, S, etc..)
- Zn-diffused, anodic oxide emitters [Sulima]
- Transparent Conducting oxides for current spreadings and ARCs [Coutts]
- Plasma-enhanced CVD of SiC [IEC]

Ceramic Substrates

- Mixtures of Al_2O_3/SiO_2 for TEC match to GaAs/Ge
- Impurity effects
- Smoothness, wetting properties of molten Ge

Epitaxy Options

GaAs: CSVT or CVD with H_2O, I_2 or HCl as transport agent
Ge: CSVT or CVD with H_2O, I_2 or HCl as transport agent
ZnSe (as a passivating layer): CVT with H_2
GaAs, AlGaAs, InGaP, GaAsP

- LPE
- Hydride or Halide CVD
- MOCVD by outside group

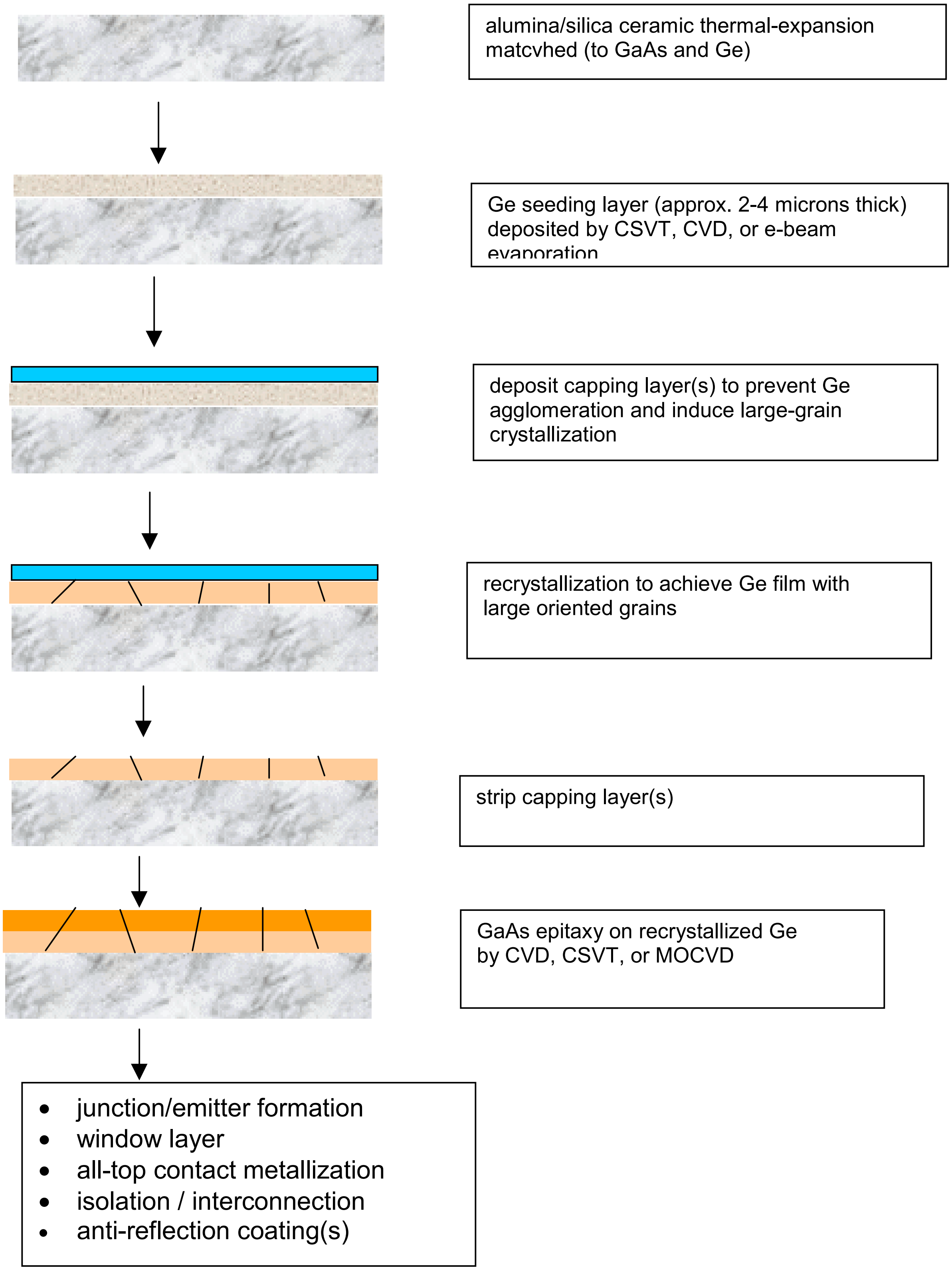
Some Criteria for Epitaxy

- Large scale: substrate size > 10-cm x 10-cm
- Atmospheric pressure operation
- No toxic precursors or by-products
- Inexpensive precursors
- Potential for continuous-mode operation
- Fast deposition rates (> 1 micron/min)
- Low capital equipment cost
- Reasonable control and instrumentation
- In-situ diagnostics
- Avoid halogens (corrosion problems, unwanted co-transport)

Some Related Applications

- InGaP / Si cells for photoelectrochemical hydrogen generation
- Large-area LEDs and detector arrays
- Space solar cell arrays

Thin-Film Poly GaAs-on-Ceramic Solar Cell Process



Reversible-Transport Reactions for Deposition of Silicon, Germanium, and GaAs and Their Applications to Solar Cells

Silicon:	$Si + I_2 \leftrightarrow SiI_2$
Germanium:	$Ge + I_2 \leftrightarrow GeI_2$
	$Ge + H_2O \leftrightarrow GeO + H_2$
GaAs:	$GaAs + H_2O \leftrightarrow GaO + \frac{1}{2} As_2 + H_2$
	$GaAs + \frac{3}{2} I_2 \leftrightarrow GaI_3 + \frac{1}{2} As_2 + H_2$

Advantages of Reversible Transport Reactions for Si, Ge and GaAs CVD

- Fast Deposition Rates (5 to 10 microns/min)
- Transport agent stored as a solid or liquid
- Recycled Transport Agent
- Atmospheric-Pressure Operation
- No Highly Toxic Precursors or Byproducts
- High-Deposition Efficiency (esp. Close-Spaced Configuration)
- Simple Control (source temp, substrate temp, transport agent conc.)
- Doping from Source

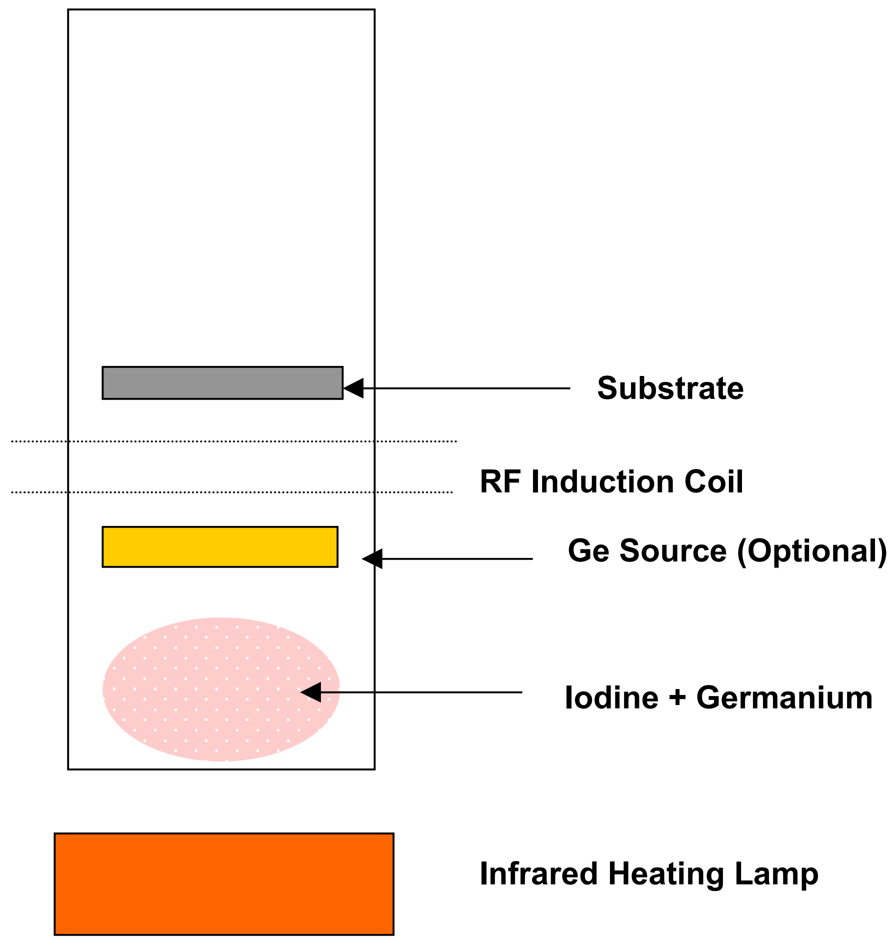
Silicon and Germanium

- Annealed / Recrystallized
- Post-Growth Gettering
- Less-Pure Solid Sources

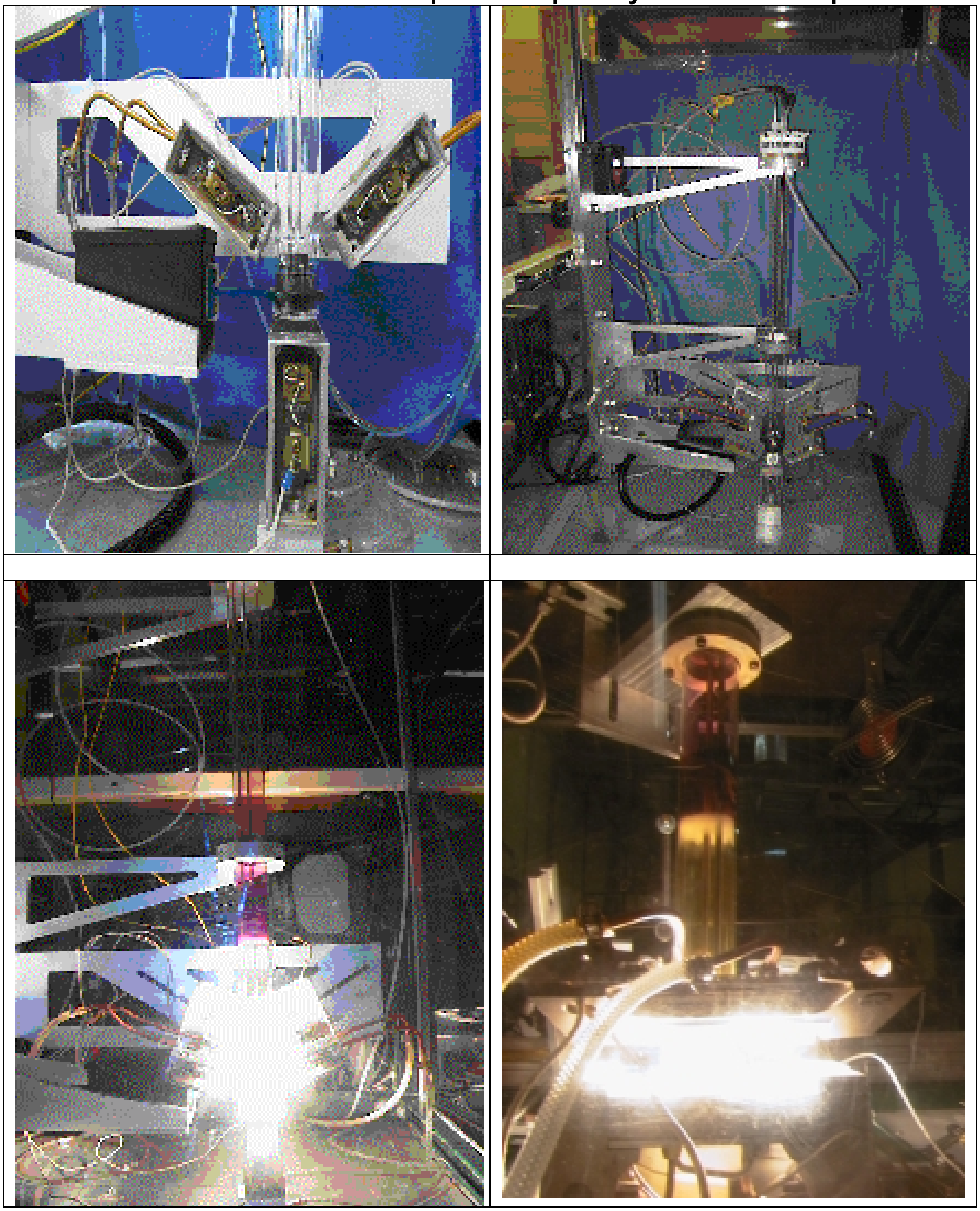
Issues

- Semiconductor Purity
- Co-Doping (from substrate)
- Grain-Size and Texture, Electrical Activity of Grain Boundaries

Vertical Tube Iodine Chemical Vapor Transport System for Depositing Ge on Ceramic Substrates

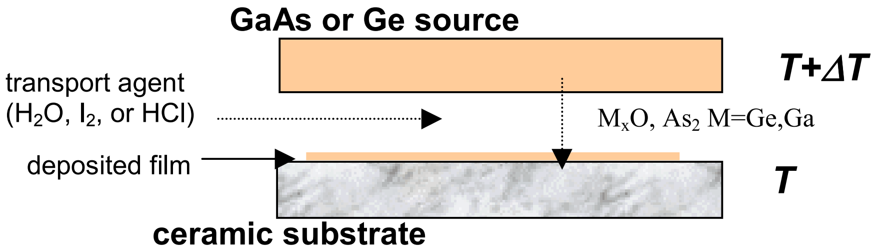


Vertical Tube Iodine Chemical Vapor Transport System for Ge Deposition

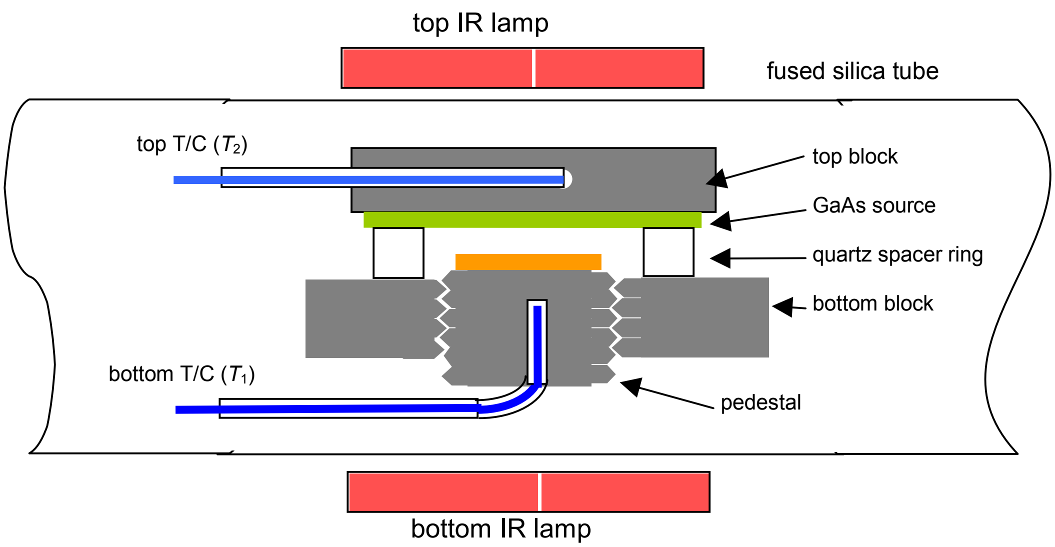


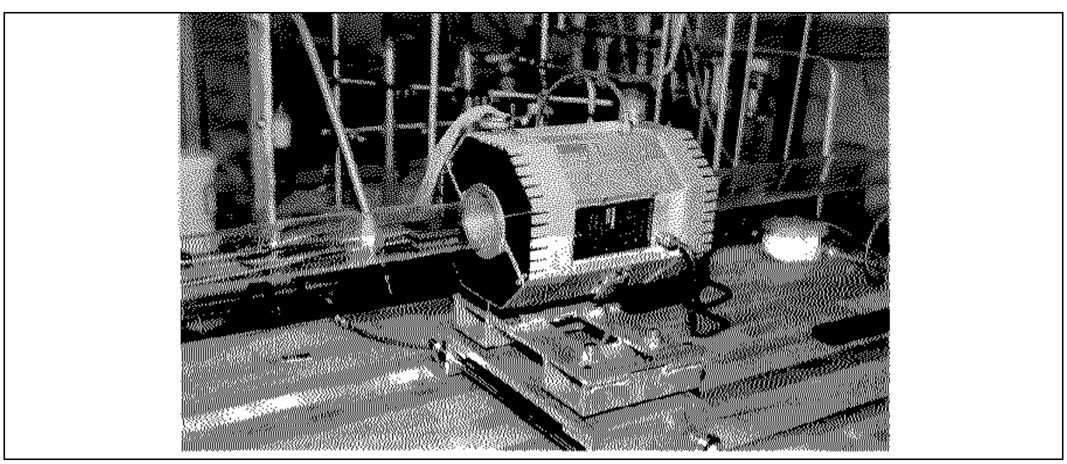
CSVT (Close-Spaced Vapor Transport)

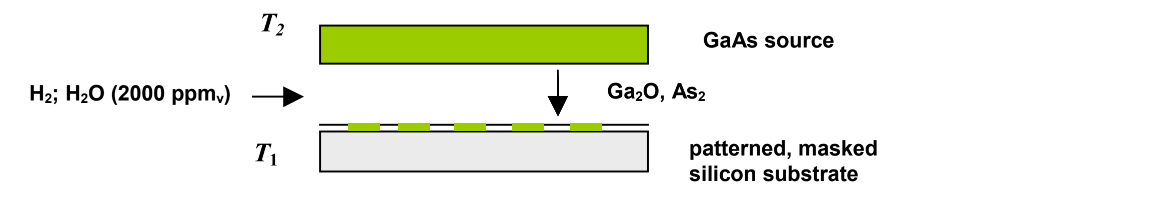
Schematic



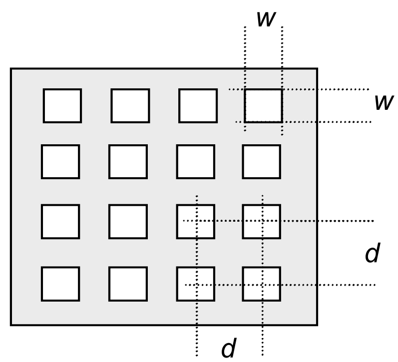
Detail



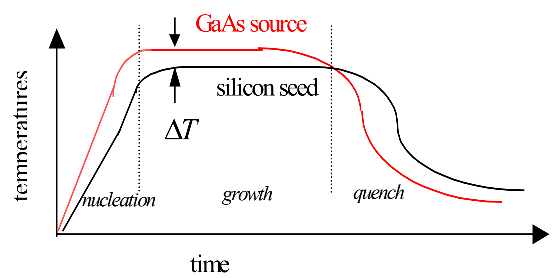




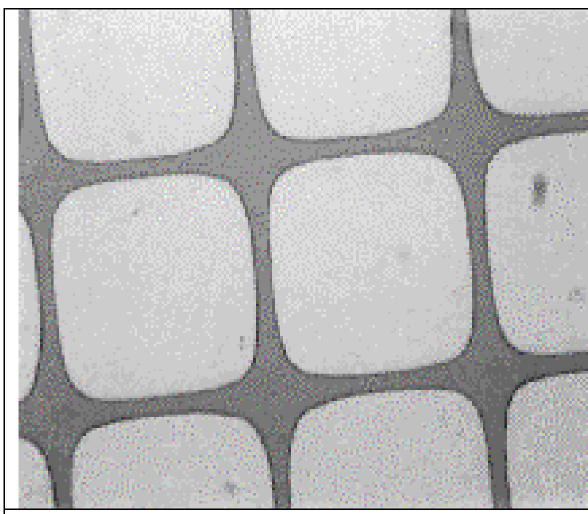
Schematic of seelctive GaAs-on-silicon CSVT process.



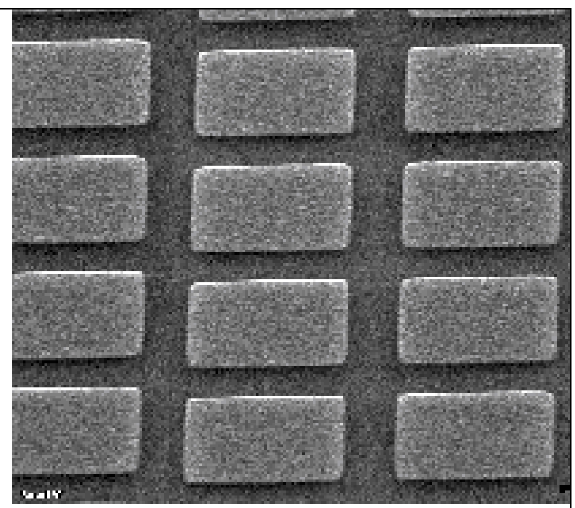
Mask geometry for selective CSVT.



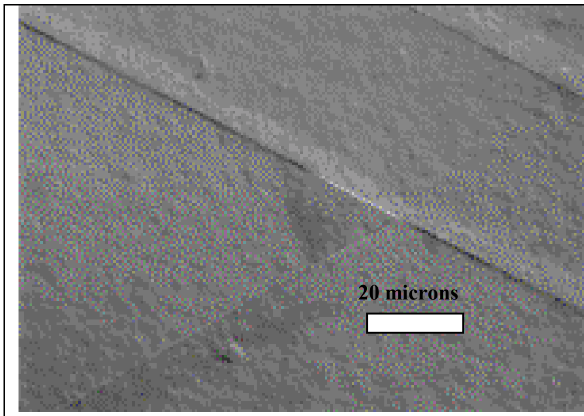
Time-temperature schedule of GaAs source and silicon seed during CSVT.



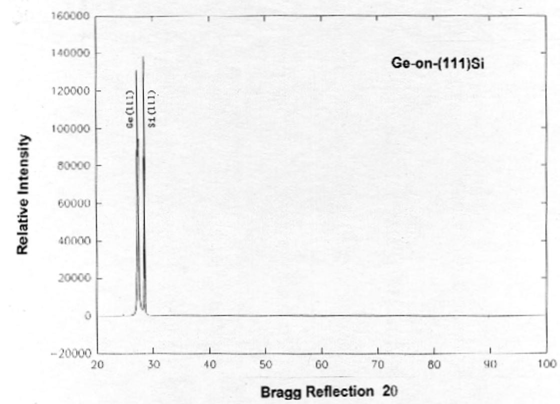
Top-view photomicrograph of selective CSVT GaAs-on-oxide-masked (111) silicon patterned with 35-micron x 35-micron windows.



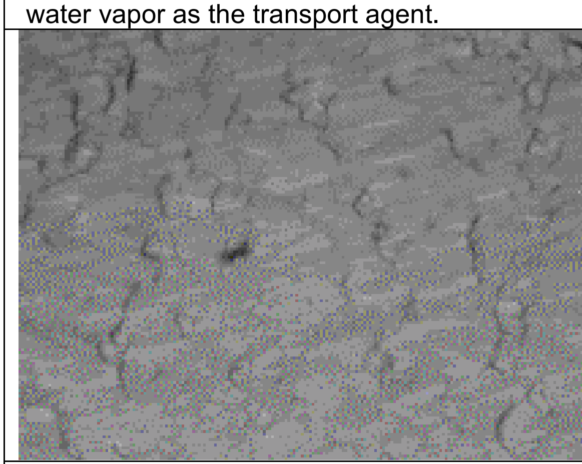
Scanning electron micrograph of CSVT GaAs-on- (111) silicon patterned into mesas by post-growth photolithography and etching.



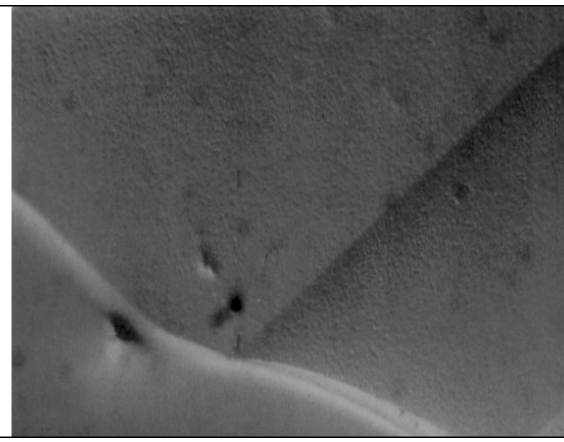
Single-crystal Ge epitaxial film grown on (111) Si by a Close-Spaced Vapor Transport (CSVT) process at 700 °C using water vapor as the transport agent.



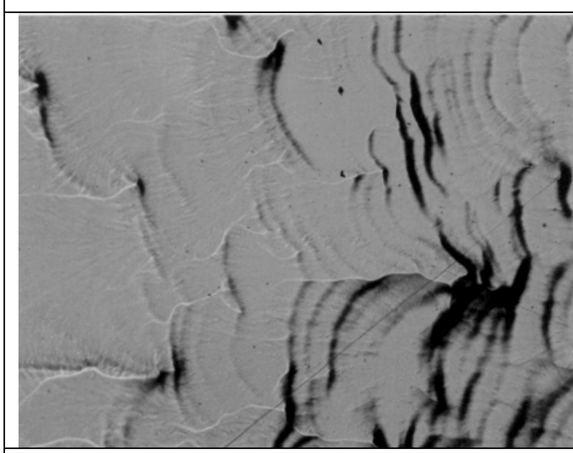
X-ray diffraction spectra of Ge-on-Silicon sample.



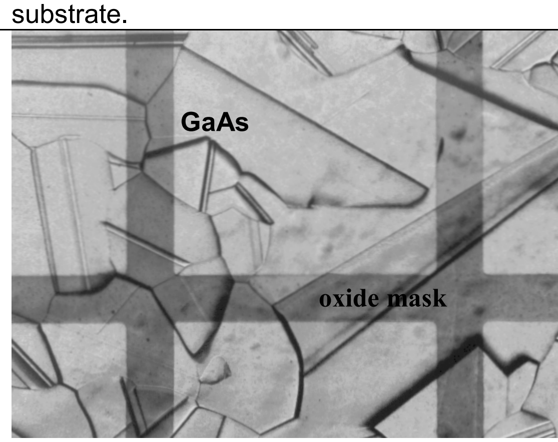
GaAs epitaxial film on polycrystalline Ge substrate grown by CSVT at 700 °C using water vapor as the transport agent.



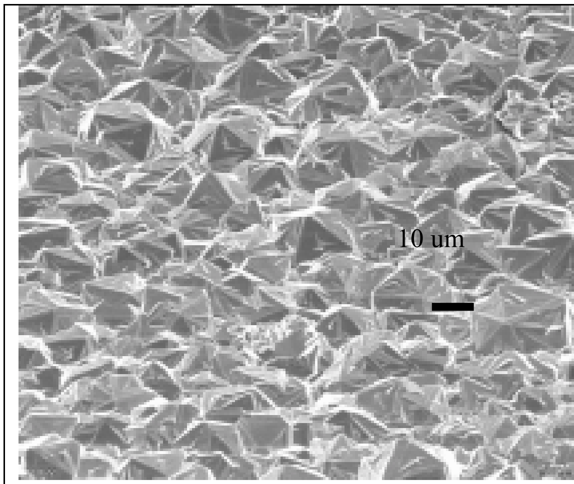
Top-view photomicrograph of a 2.5-micron thick Ge layer grown by CSVT on a Silicon-Film™ polycrystalline silicon sheet substrate.



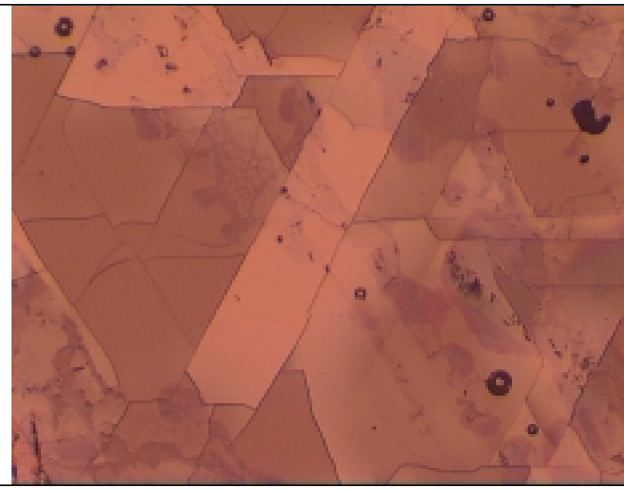
Top-view photomicrograph of4-micron thick Ge layer grown on a Silicon-Film™. Ge layer has been melted and recrystallized by annealing the sample at 950 °C in hydrogen for one-hour.



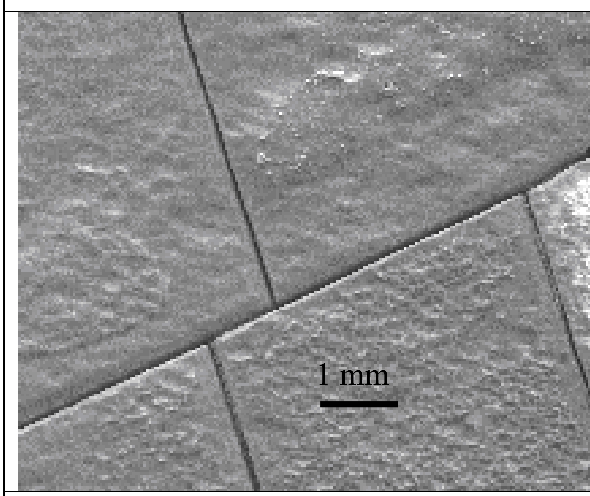
Top-view photomicrograph of selective CSVT GaAs on a Silicon-Film™ polycrystalline silicon sheet substrate. Squares are 500 microns x 500 microns.



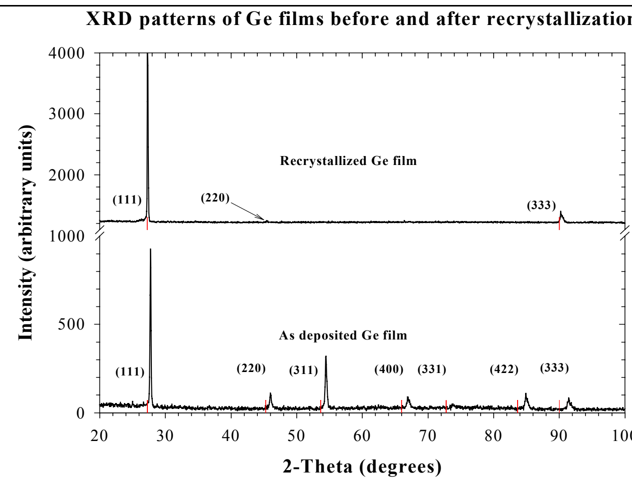
Scanning electron micrograph of as-deposited Ge film on alumina ceramic substrate.



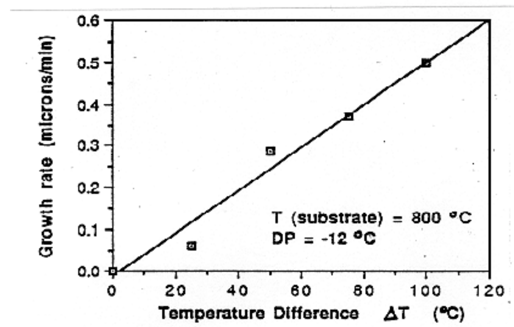
Top-view photomicrograph of recrystallized 5-micron thick Ge film on fused silica substrate.



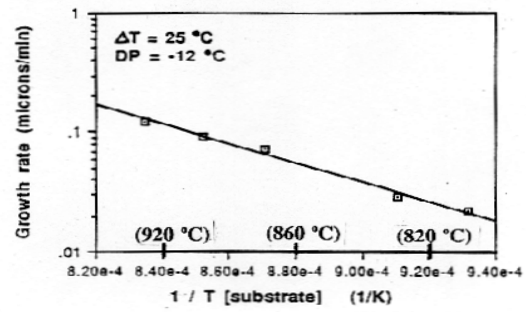
Scanning electron micrograph of recrystallized Ge film on fused silica substrate.



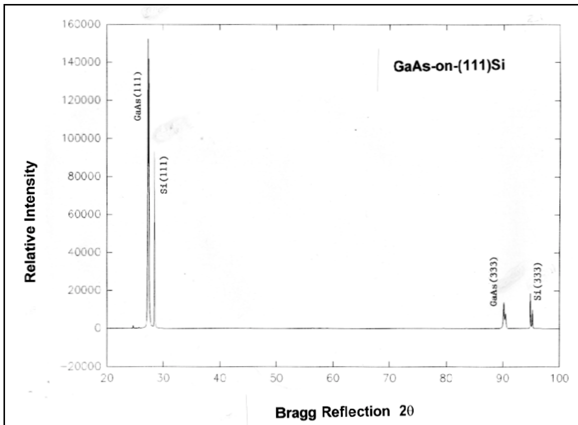
X-ray diffraction of Ge films before and after recrystallization.

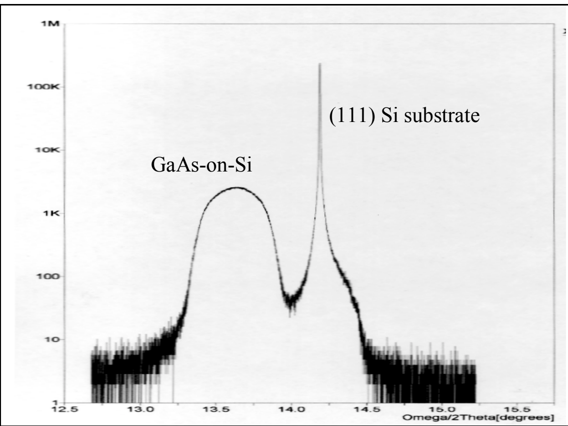


GaAs-on-Si CSVT kinestics
as a function of temperature difference ΔT
between source and seed.

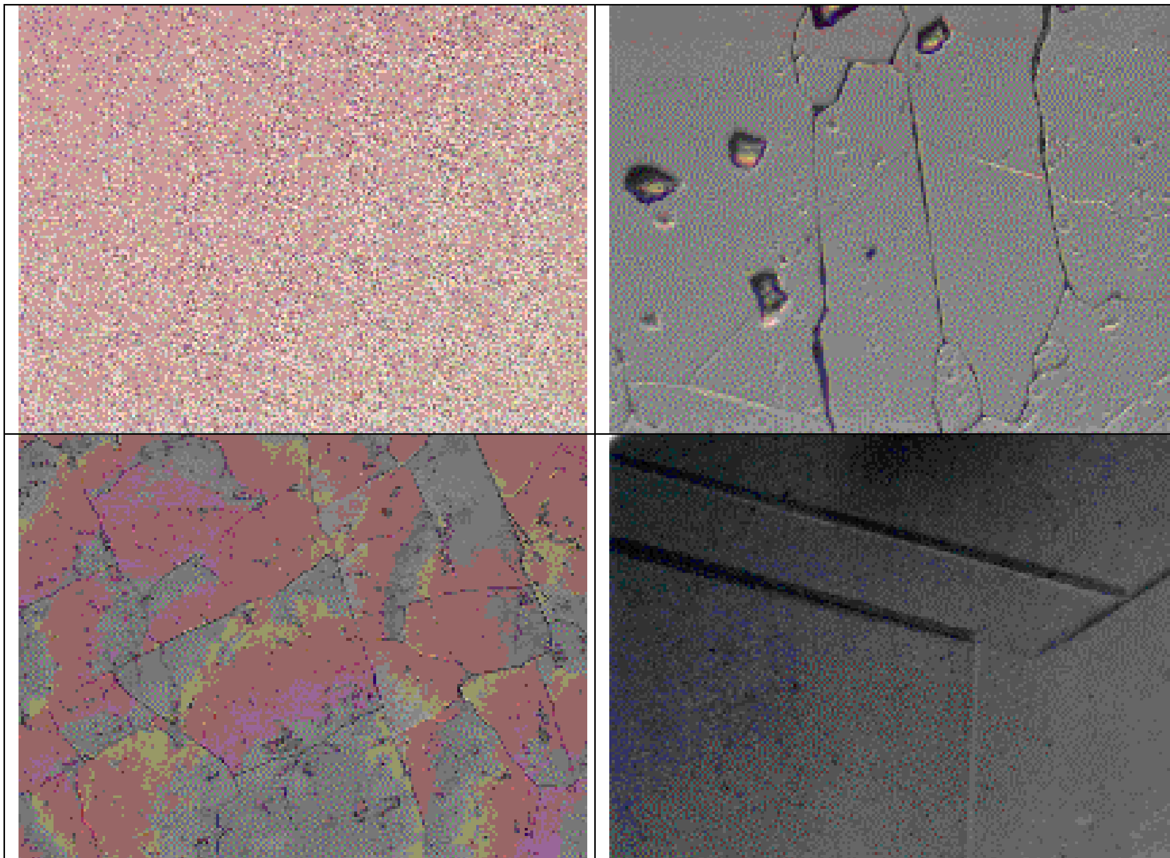


Log of growth rate vs.
reciprocal of substrate temperature for
GaAs-on-Si CSVT.





X-ray diffraction spectra for 0.4-micron thick GaAs-on-silicon films made
by CSVT. **a.** wide scan, low resoluton, **b.** double-crystal rocking curve.



National Renewable Energy Laboratory

High-Performance Photovoltaic Project

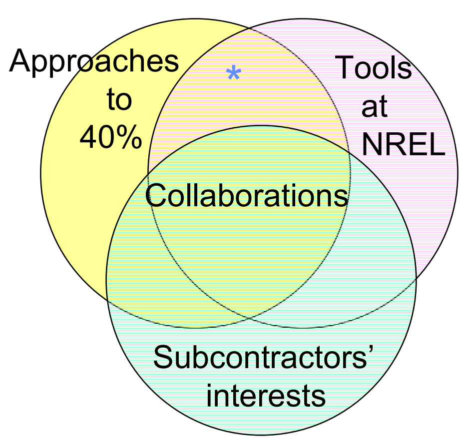
NREL Basic Research Toward a 40% Efficiency

Sarah Kurtz

High-Performance PV Kickoff Meeting

October 18, 2001

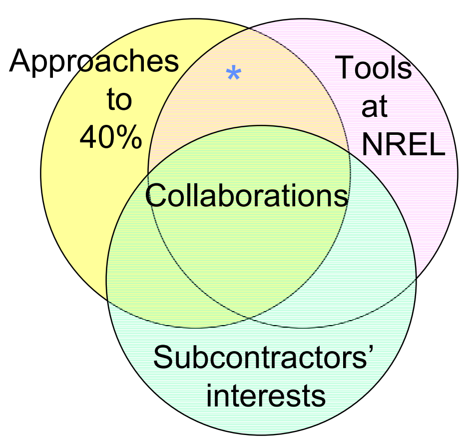
Where we fit in the big picture



Opportunities for collaborations between NREL and subcontractors

- TEM - characterization of mismatched layers
  - Mowafak_AlJassim@nrel.gov (303)384-6602
- Cell and module measurements
  - Keith_Emery@nrel.gov (303)384-6632
- Characterization (TRPL, DLTS, FTIR, SIMS, etc.)
  - www.nrel.gov/measurements
  - Pete_Sheldon@nrel.gov (303)384-6533
- Resource assessment (spectrum of direct beam) and how it affects cell design (AM1.5Direct is *not* appropriate for outdoor concentrator measurements)

Where we fit in the big picture



Dilute-nitrogen alloys

(GaInAsN, etc.)

(one of many possible approaches)

Problem = Photovoltaic quality is degraded by nitrogen

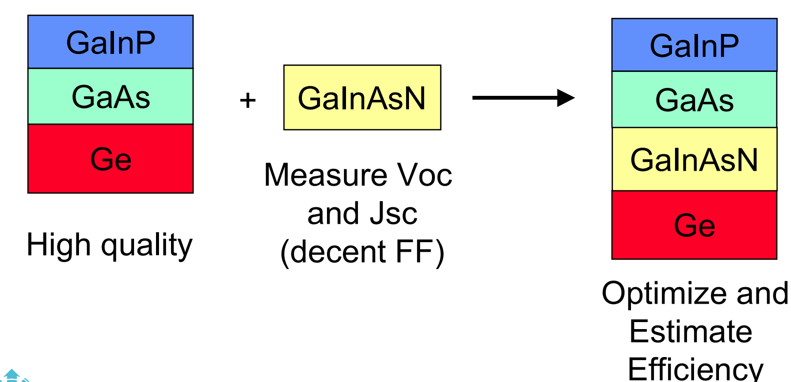
Reasons for studying this approach:

- GaInP/GaAs/GaInAsN/Ge theoretically > 50%
- GaInP/GaAs/GaInAsN/Ge is similar to GaInP/GaAs/Ge
- “best” GaInAsN cells are close to “break even”
- This basic research problem is well matched to NREL’s mission and strengths

NREL

Breakeven calculation - approach

(Friedman)

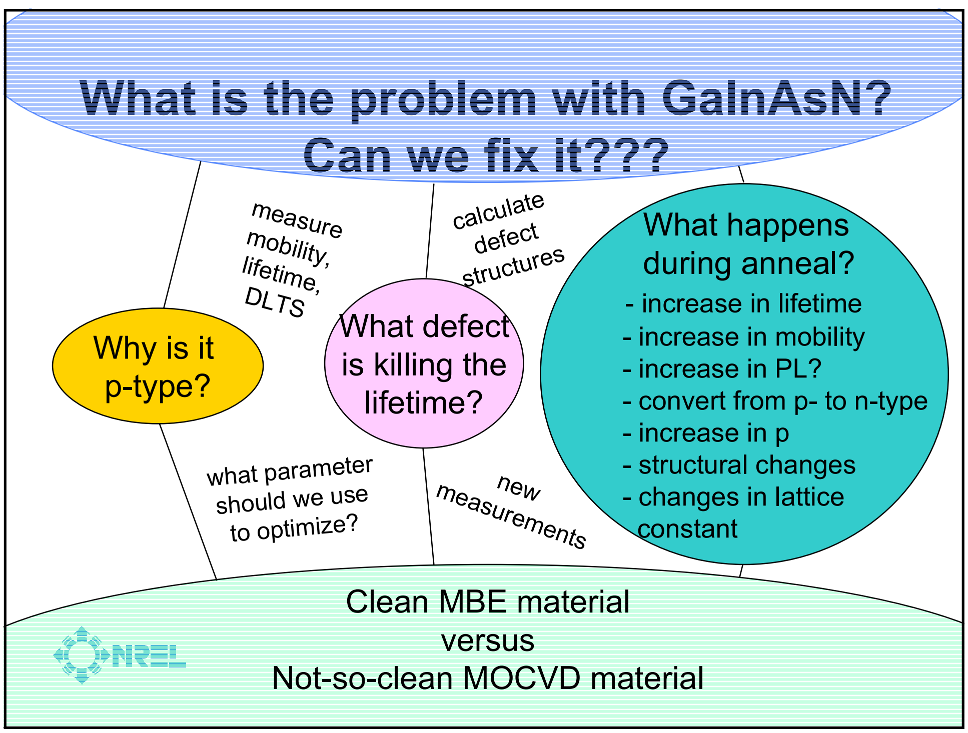


NREL

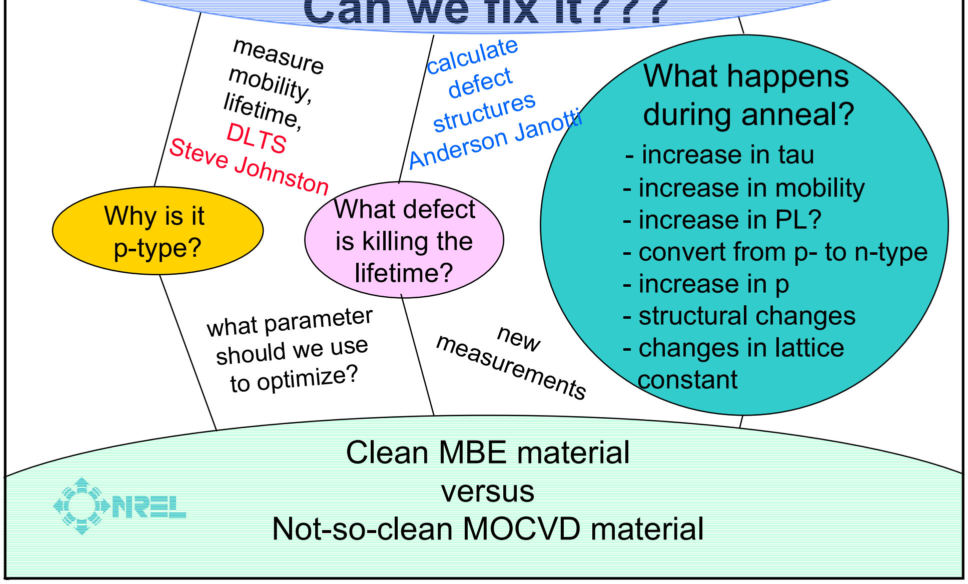
Breakeven calculation - results
(Friedman)

Conditions	Expected 3-junc. Efficiency (no series res.)	Estimated 4-junc. Efficiency with best GaInAsN
AM0 – 1 sun	29.9%	28.2%-29.4%
AM1.5 Global (500 suns)	40.2%	38.6%-39.7%
AM1.5 Direct (500 suns)	38.2%	39.1%-40.5%

Conclusion: optimist - we're almost there
pessimist - it's not hopeless



What is the problem with GaInAsN? Can we fix it???



Discussion topics

- Collaboration on materials measurements
- Spectral issues
- Stability/degradation issues (heat, high current, intense light; will it last for 30 years?)

Reference Conditions for PV Concentrators?

Keith Emery
National Renewable Energy Laboratory
1617 Cole Blvd., Golden CO 80401
email: keith_emery@nrel.gov

Concentrator Standards

Cells - From ISE, NREL, Sandia, Progress in PV
- 25 °C, 1-sun = 1000 W/m^2 total irradiance
- ASTM E891 direct normal spectrum (767 W/m^2 direct)
- Area = total area minus peripheral bus bars

Modules -
- Area = lens/mirror aperture area
- Prevailing spectral irradiance, 850 W/m^2 total direct irradiance, 20 ° air temperature
- (ASTM draft E130, PVUSA, IEEE 1513)
- Prevailing spectra corrected to AM1.5, 850 W/m^2 direct irradiance,150 W/m^2 diffuse irradiance, 50 °C cell temperature, (IEEE 1513)

National Center for Photovoltaics

Outline - What is the Problem?

The direct normal reference spectrum is not representative of locations where concentrators might be deployed?

Measurements & Characterization Division

National Center for Photovoltaics

When 2-axis global 1001 W/m^2 (σ=1.3)

834 W/m^2 direct irradiance (σ=22.8)

24.4 °C air temperature (σ=4.0)

4.4 m/s wind speed (σ=1.1)

0.08 turbidity @ 500 nm (σ=0.02)

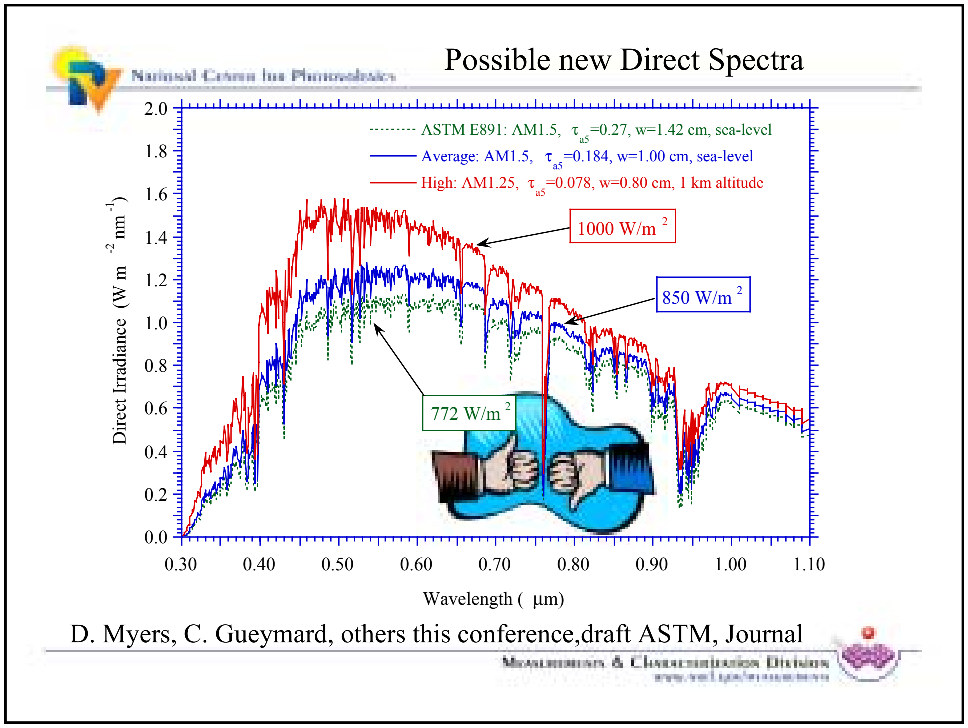
1.43 relative optical Air Mass (σ=0.09)

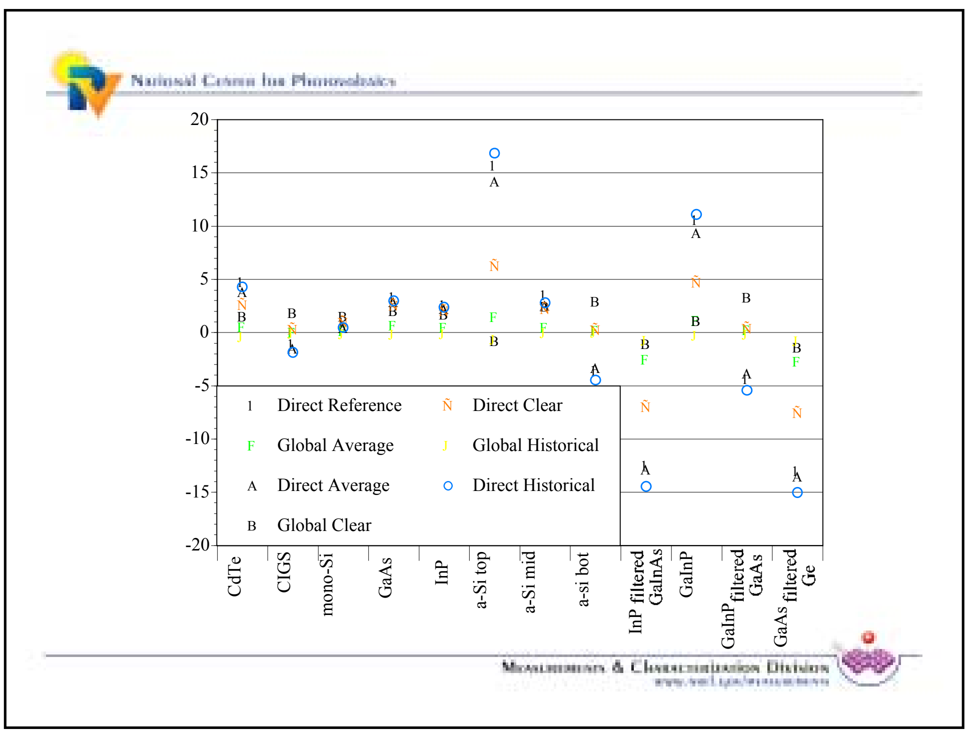
37 sites in southwest U.S. 433,562 observations

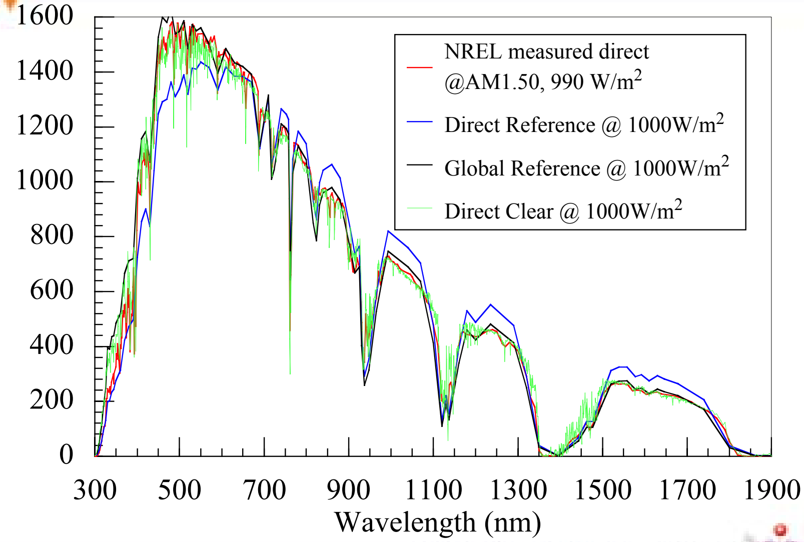
D. Myers et al., *Proc. 28th IEEE PVSC.*, p. 1202, 2000.

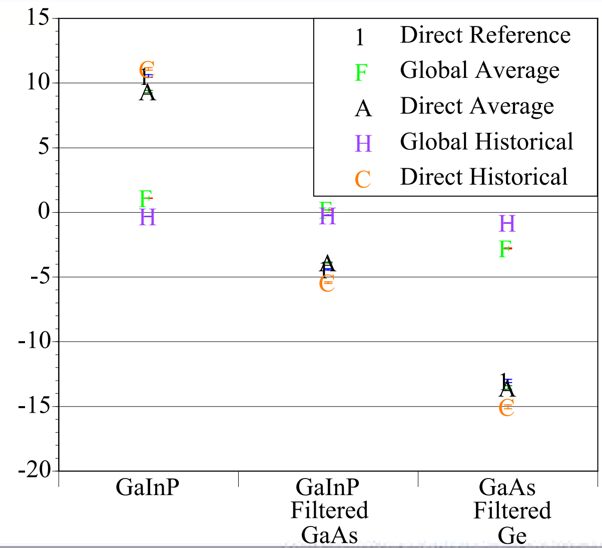
Not enough “blue” in ASTM E891 direct because turbidity of 0.27 used.
Total irradiance of 767W/m^2 for E891 is too low

Measurements & Characterization Division


National Center for Photovoltaics
Possible new Direct Spectra
ASTM E891: AM1.5, τa5=0.27, w=1.42 cm, sea-level
Average: AM1.5, τa5=0.184, w=1.00 cm, sea-level
High: AM1.25, τa5=0.078, w=0.80 cm, 1 km altitude
1000 W/m 2
850 W/m 2
772 W/m 2
Direct Irradiance (W m -2 nm -1)
Wavelength (µm)
D. Myers, C. Gueymard, others this conference,draft ASTM, Journal
Measurements & Characterization Division


National Center for Photovoltaics
Direct Reference
Direct Clear
Global Average
Global Historical
Direct Average
Direct Historical
Global Clear
CdTe
CIGS
mono-Si
GaAs
InP
a-Si top
a-Si mid
a-si bot
InP filtered GaInAs
GaInP
GaInP filtered GaAs
GaAs filtered Ge
Measurements & Characterization Division


NREL measured direct @AM1.50, 990 W/m2
Direct Reference @ 1000W/m2
Global Reference @ 1000W/m2
Direct Clear @ 1000W/m2
1600
1400
1200
1000
800
600
400
200
0
300
500
700
900
1100
1300
1500
1700
1900
Wavelength (nm)


1 Direct Reference
F Global Average
A Direct Average
H Global Historical
C Direct Historical
15
10
5
0
-5
-10
-15
-20
GaInP
GaInP Filtered GaAs
GaAs Filtered Ge

The spectral sensitivity of single junction devices (Si, GaAs) is not more than ±2% under a wide variety of conditions.

In "real world" concentrator modules GaInP/GaAs/Ge cells optimized for the AM0 or global spectrum consistently outperform cells optimized for the direct spectrum

Concentrator cell 34.0% for global 30.6% for direct spectrum

National Center for Photovoltaics

Where do we go from here?

Concentrator modules will be evaluated outdoors under prevailing clear-sky conditions without a correction to the existing direct reference spectrum. At most a correction to AM1.5 (IEEE).

Cells for concentrator modules should be optimized for maximum module efficiency (direct average or global reference).

Report concentrator cell efficiencies under the global and direct reference spectrum.

Measurements & Characterization Division

National Center for Photovoltaics

Where do we go from here?

Get the standards labs together (in person or via email) to make a decision to change the direct reference spectrum to reflect a more realistic turbidity.

Get the U.S. concentrator industry and the national labs (Sandia and NREL) to reach a consensus on what to do.

Measurements & Characterization Division

High Performance, Low Cost III-V PV Concentrator Module

Raed A. Sherif & Richard R. King

October 18, 2001

Goal & Work Scope

- Identify the critical paths towards achieving a 33% module conversion efficiency at $1 per Watt.

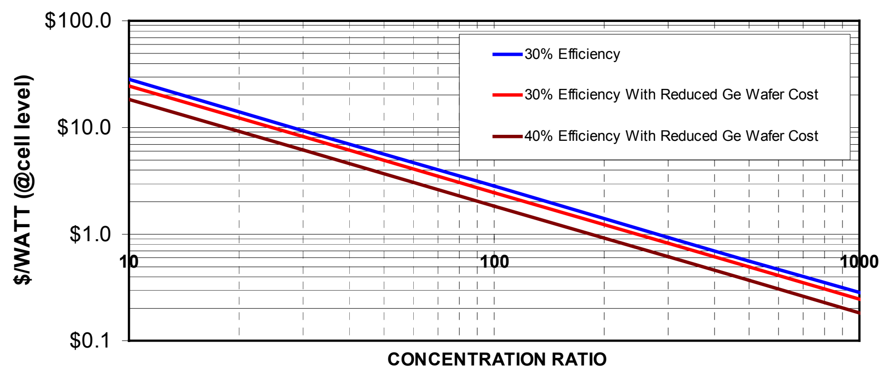
- A two-year effort investigating:

  - How to increase III-V PV cell conversion efficiency
  - How to make III-V PV cells more robust for high concentration
  - How to reduce the manufacturing costs of III-V PV cells
  - Module designs that are low cost, yet reliable, and have low thermal resistance to the cooling fluid.

Cost Reduction Approaches for III-V PV Cells

SPECTROLAB

1. Increase PV cell conversion efficiency & reduce its manufacturing cost
2. Use higher concentrations



Specific Objectives in this framework

SPECTROLAB

- PV Cell
  1. Develop a high efficiency (> 32%) monolithic multijunction PV concentrator cell
  2. Develop a very high efficiency (> 35%) integrated multijunction PV concentrator cell using two or more different substrates.
  3. Develop a robust cell structure and metallization scheme that eliminates cell shunting under high concentration.
  4. Research low-cost substrates for high efficiency multijunction cell growth.
  5. Added task: deliver 100 concentrator cells (~ 1x4 cm) to operate at ~ 440 suns average with maximum concentration of ~ 1600 suns on 1/4 of the cell.
- PV Receiver
  1. Identify designs that have potential for low cost, high performance and good reliability
  2. Build prototypes and demonstrate their performance and reliability

High Efficiency Cell Development Work Scope

SPECTROLAB

- Develop a high efficiency concentrator cell (> 32%) by leveraging PV technology used in space applications.
  - Triple junction cells: GaInP/ GaAs/ Ge
  - Metamorphic triple junction cells: GaInP/ GaInAs/ Ge
  - Four junction cells: GaInP/ GaAs/ GaInNAs / Ge

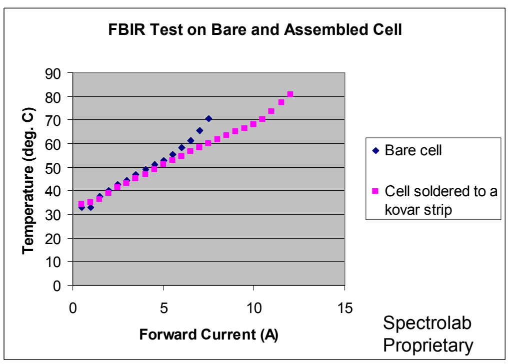
- Demonstrate new prototype cell designs using an integrated cell approach (wafer bonding or mechanical stacking) to achieve ultra-high cell efficiency (> 35%)
  - Baseline: GaInP/ GaAs/ Si
  - Additional examples: GaInP/ GaAs/ Si/ GaSb
    GaInP/ GaAs/ GaInPAs/ GaInAs
  - Two terminal, 3-terminal, and 4-terminal MJ cell designs

Spectrolab Proprietary

Increased Cell Robustness- Interaction with Thermal Management

SPECTROLAB

- Investigate metallization structures that can increase cell robustness to shunting.
- Investigate impact of highly non-uniform flux on a cell level
- Investigate interaction between how a cell is cooled and its current carrying capability.



Spectrolab Proprietary

Module Design

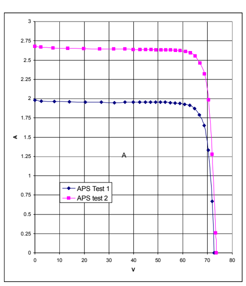
- **Goal is to have a module design that is:**
  - **- Low cost**
  - **- Enables high concentration**
  - **- Enables mechanized assembly, inspection, and test.**

- Identify tradeoffs in module cost, thermal management, and thermal expansion mismatches.

- Investigate different types of designs:
  - Single cell vs. densely packed array designs
  - Active vs. passive cooling
  - Which design(s) are more compatible with mechanized assembly, inspection, and test.

- Define an appropriate test vehicle for testing cells under high concentration.

A Dense PV Array for 2 kW Output at 300 sun Concentration



Collaboration between Spectrolab, APS, and Concentrating Technologies

Tasks & Schedule for Cell Development (Year I)

SPECTROLAB

• MJ cell electrical modeling input for cell growths	Nov '01
• ~150 cm^2 of conc. cells delivered to ENTECH (100 cells with ~1.5 cm^2 aperture area)	Dec '01
• Receive alternative low-cost Ge substrates	Jan '02
• GaInP / GaAs / Ge and GaInP / GaInAs / Ge cell sample delivery	Mar '02
• GaInP / GaAs cell bonded to Si substrate sample delivery	Jul '02
• GaInP / GaAs cells without metallization for collaboration with NREL on mech. structures	Jul '02

Tasks & Schedule for Receiver Development (Years I&II)

SPECTROLAB

• Thermal, thermal stress, electrical and cost modeling for concentrator cells and modules.	Nov' 01
• Preliminary design definitions of prototypes and test vehicle	Dec' 01
• Parts procurement and fabrication	Apr' 02
• Build test vehicle	Jun' 02
• Cell design and fabrication	Oct' 02
• Build prototype	Mar' 03
• Demonstrate performance and reliability	Jul' 03

DEVELOPMENT OF TERRESTRIAL CONCENTRATOR MODULES USING HIGH-EFFICIENCY MULTI-JUNCTION SOLAR CELLS

Funded in Part by NREL/ENTECH Subcontract No. ADJ-1-30620-02

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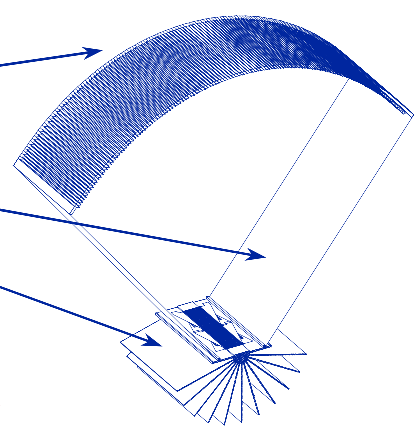
ENTECH, INC.

Slide 1 - High-Performance Kick-Off Meeting at NREL 10/18/01

Background: ENTECH's 4th Generation Module

- **Fresnel Lens:**
  - 3M-Produced Acrylic Lens
  - 0.8 m Wide by 3.7 m Long Aperture = 3 sq.m. Total
- **Marine Aluminum Housing**
  - 2 Sidewalls and 2 Endplates
- **Photovoltaic Receiver:**
  - 37 Diode-Protected, Prism-Covered Cell Packages
  - Full-Receiver Dry Tape & Film Laydown & Encapsulation
  - Extruded Aluminum Heat Sink



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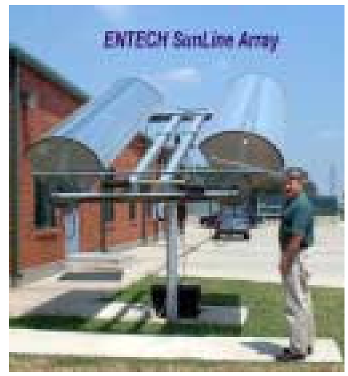
Slide 2 - High-Performance Kick-Off Meeting at NREL 10/18/01

Background: ENTECH's Solar Arrays

Field-Proven 72-Module SolarRow Array for Large Power Plants and 2-Module SunLine Array for Small Applications



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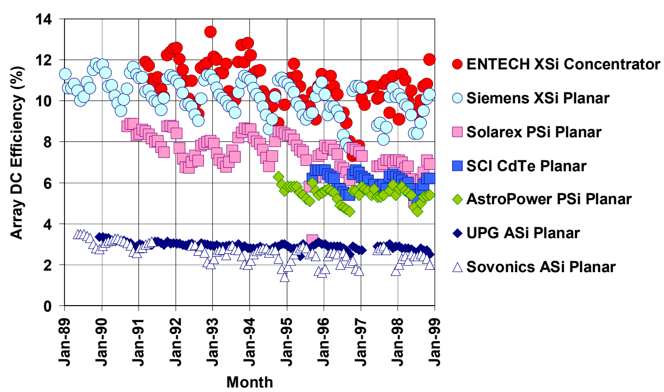
Background: Independent Long-Term Performance Data

PVUSA Array Monthly Efficiency Data at Davis, CA



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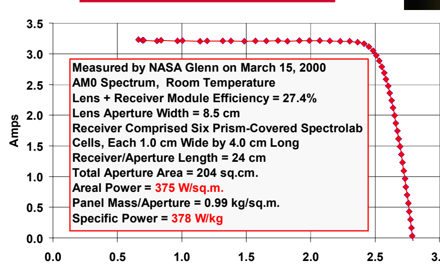
Background: ENTECH Space Concentrators

- ENTECH Has Been Developing Fresnel Lens Concentrators for Space Power for NASA and DOD Since 1986
- Most Recently, the Deep Space 1 SCARLET Array Powered Both the Spacecraft and the Ion Engine for the Last 3 Years, Resulting in a Spectacular Comet Rendezvous Sept. 22, 2001
- Fresnel Lenses Over Triple-Junction Cells Have Performed Flawlessly

ENTECH, INC.

Background: Space Stretched Lens Array (SLA)

NASA-Measured Performance Is Unprecedented

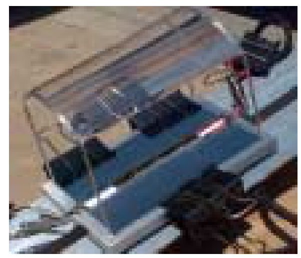


Ultra-Light Concentrator Array Weighs Much Less per Unit Area than a One-Sun Cell Alone

ENTECH, INC.

Synergy Between Space and Ground Concentrators

- Space Stretched Lens Modules with Space Multi-Junction Cells Perform Spectacularly Outdoors Under Terrestrial Sunlight
- All Three Modules Below Exceed 27% Operational Efficiency
- NREL Confirmed Left Module as World-Record Holder

Spectrolab Cell	*EMCORE Cell*	*TECSTAR/JX Crystals Cells*
		

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Slide 7 - High-Performance Kick-Off Meeting at NREL 10/18/01

ENTECH's High-Performance Module Development

- Since 1999, We Have Been Working on the Development of Terrestrial Concentrator Modules Using Multi-Junction Cells
- Our Proprietary New 440X MJ Cell-Based Module Will Be a Plug-and-Play Replacement for Our Silicon-Based 21X Module, Enabling Use of Proven SunLine and SolarRow Arrays
- Secondary Optics Will Focus Sunlight in the Longitudinal Direction by Another 21X, Resulting in a 440X Overall Concentration
- Prototype Testing Indicates that Optical and Thermal Issues Are Technically and Economically Solvable for the New Module
- However, Cell Issues Remain, But Non-Disclosure Agreements with Cell Suppliers Prevent Open Discussion of Details on These Issues

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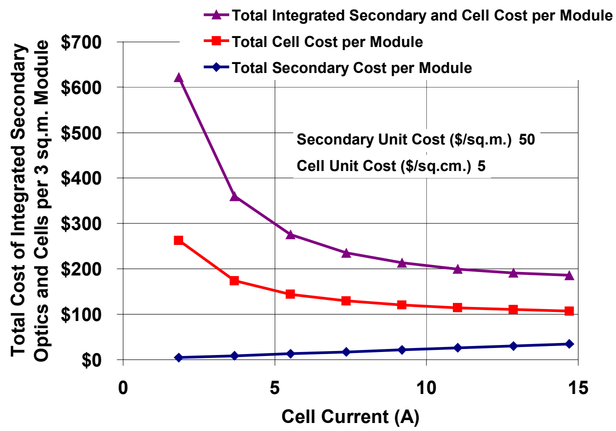
Slide 8 - High-Performance Kick-Off Meeting at NREL 10/18/01

We Need High-Current Cells for Good Economics

Space Cells All Operate Well Under 1 Amp - We Need Cells to Operate Above 10 Amps



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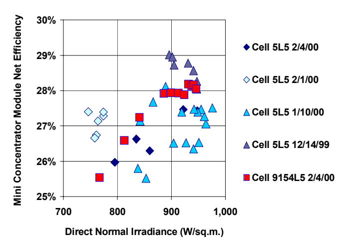
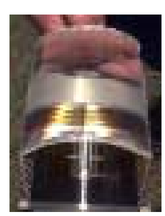
Slide 9 - High-Performance Kick-Off Meeting at NREL 10/18/01

Spectral Issues

- Cells Designed for AM0 Perform Exceptionally Well in Outdoor Tests Under All Sorts of Conditions
- Using Quantum Efficiency Curves for AM0-Designed Cells and the AM1.5D Spectrum, the Middle Junction (GaAs) Should Have a 38% Higher Current than the Top Junction (GaInP), Making Our Excellent Outdoor Test Results Impossible
- This Spectral Problem Is Causing Confusion Among All the Cell Suppliers and Needs to Be Quickly Resolved by Abandoning AM1.5D





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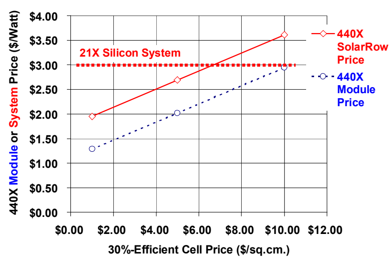
Slide 10 - High-Performance Kick-Off Meeting at NREL 10/18/01

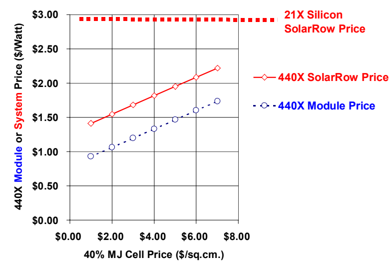
Near-Term and Long-Term Economics

Higher Cost of Higher Concentration (Secondary Optics, Heat Spreaders, More Parts per kW) Demands Major Boost in Efficiency Over Silicon

Near-Term: 30% Cell



Long-Term: 40% Cell



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Slide 11 - High-Performance Kick-Off Meeting at NREL 10/18/01

On-Going Work and Key Issues

- **Optimize Operational Current Level for Multi-Junction Cells**
  - **Is There an Upper Current Limit for Durability?**
- **Optimize 440X Module Optics, Including Color-Mixing Lenses**
  - **Sizing Depends on Current Level Mentioned Above**
- **Optimize 440X Module Cells**
  - **What Spectrum Is Appropriate for Current-Matching the Junctions?**
- **Optimize a Robust 440X Photovoltaic Receiver**
  - **What Caused Recent Boeing and Loral Array Problems on Orbit?**
- **Build and Test Full-Size 440X Concentrator Module & SunLine**
  - **Schedule Depends on Previous Items**
- **Commercialize 440X SolarRow and SunLine Systems**
  - **What Price/sq.cm. Can Multi-Junction Cells Reach?**

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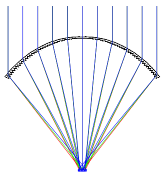
Slide 12 - High-Performance Kick-Off Meeting at NREL 10/18/01



Recommendations Relating to Multi-Junction Cells

As Concentrator Module Developers and Manufacturers, We Need Help from Cell Suppliers and NREL in Two Key Cell Areas

- **Solar Spectrum**
  - **Near-Term: Cell Suppliers Should Optimize Cells for AM1.5G or AM0, Not AM1.5D, Which Is Not Realistic**
  - **Mid-Term: NREL Should Consider Deploying Triple-Head Pyrheliometers (GaInP, GaInP-Filtered GaAs, and Black Body Sensors) at Various Sites Around the U.S. and Collect Data**
- **Cell Durability**
  - **Near-Term: NREL Should Consider Coordinating Efforts with Spectrolab, EMCORE, TECSTAR, JX, and Other Cell Suppliers to Address Common Issues (Current Limits, Reverse Bias Effects, Transient Effects, Long-Term [30 Years] Durability in Terrestrial Environment, etc.)**

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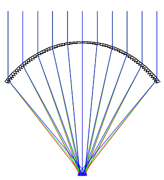
Slide 13 - High-Performance Kick-Off Meeting at NREL 10/18/01



Conclusions

- **We Have Already Seen Cell Efficiencies Above 30% and Operational Mini-Module Efficiencies Above 27% in Outdoor Tests of Low-Concentration Space Lenses Over Space Cells**
- **These High Efficiencies Could Lead to Outstanding System-Level Economics, If Remaining Issues Are Resolved**
- **Significant Cell Issues Remain to Be Addressed:**
  - **Performance Under High, Non-Uniform Concentration**
  - **Absolute Current Limits Consistent with 30-Year Life**
  - **Durability Under Continuously Transient Conditions for 30-Year Life**
  - **Cell Package Cost, Including Interconnects, Heat Spreader, Bypass Diode, Encapsulation, etc., Must Be << $10/sq.cm. (Current Space)**
  - **Potential Customers Always Ask for Long-Term Field Data**

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Slide 14 - High-Performance Kick-Off Meeting at NREL 10/18/01

A 3J Solar Cell for High Concentration Terrestrial Applications

Mark A. Stan

Emcore Photovoltaics

10420 Research Road, SE

Albuquerque, NM 87123

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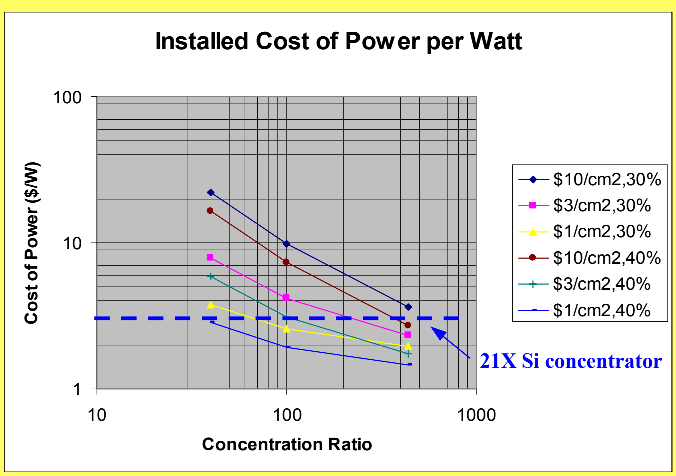
Concentrator System Cost Dependencies



* System model courtesy of M. O'Neill (ENTECH)

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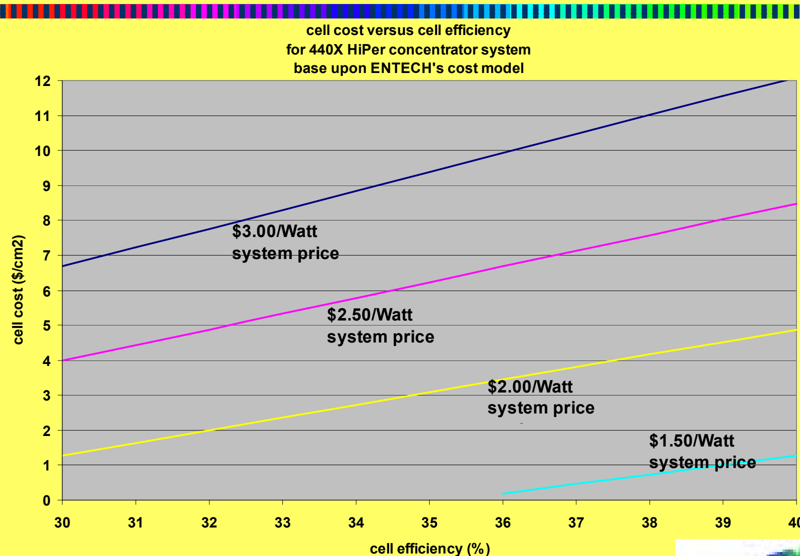
System Cost Dependence of cell cost and efficiency



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Present State-of-the-Art two-terminal MJ concentrators

Embodiment of Concentrator	Supplier	Spectrum	Concentration Ratio	Test Method	Efficiency
L-M InGaP/GaAs/p-Ge (3J)	Spectrolab	AM1.5D	372	Pulsed	32.40%
L-M InGaP/GaAs/n-Ge (2J)	Spectrolab	AM1.5D	160	Pulsed	29.60%
L-MM InGaP/InGaAs/ GaAs (2J)	Fraunhofer	AM1.5D	300	Pulsed	31.30%

* Efficiency numbers assume spectral accuracy

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Technical Approach

- Target > 40% cell design for 400X-500X concentration.
- Leverage knowledge of 3J growth on Ge with Lattice-mismatched III-V materials technology presently used by Emcore for Thermophotovoltaic (TPV)devices.
- Device modeling to be performed by Dan Aiken (Emcore) & Prof. Jeffery Gray at Purdue University to determine optimum concentrator cell structure.
- On-sun receiver performance measurements will be made by Amonix.

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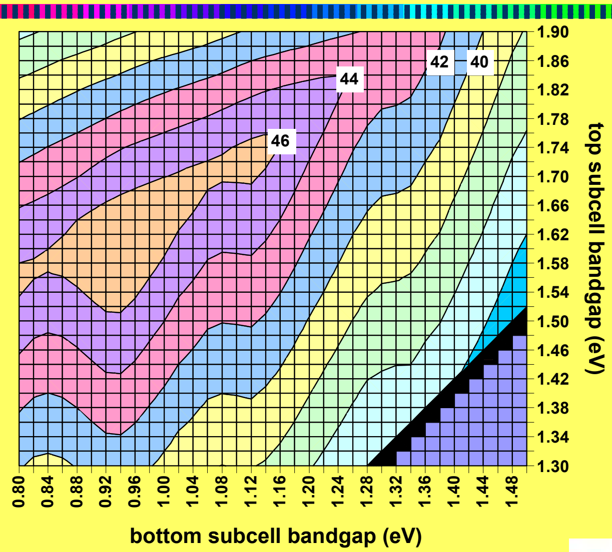
Isoefficiency Plot for 400X Concentration Ratio



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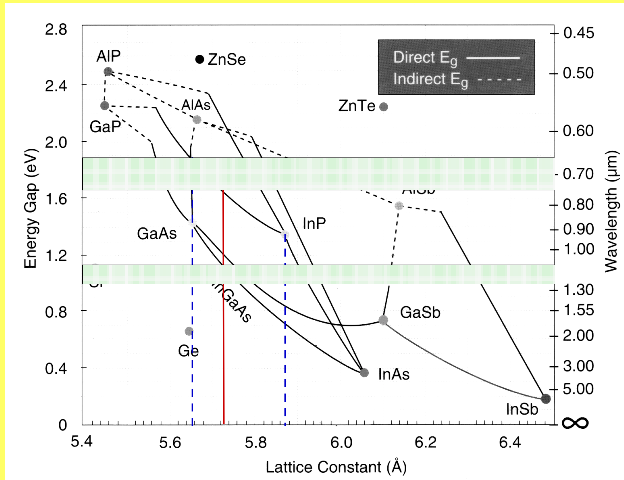
Crystal Growth Chart w/ Optimal Bandgap combinations



Anticipated Issues for Success of Lattice-Mismatched Cells

- **Development of lattice constant grading buffer structure from Ge to $In_xGa_{(1-x)}As$ (0<X<0.2)**
  - **must minimize threading dislocation density**
  - **Benchmarks on GaAs**
    - » **21.6% (AM1.5G) n/p $In_{0.17}Ga_{0.83}As$ (Fraunhofer)**
    - » **Voc=786 mV, Jsc=36.4 mA/cm^2, FF=79%**

- **Development of a high peak current density tunnel diode**
  - **500X requires Jp=8 A/cm^2**
  - **Fraunhofer AlGaAs/InGaP diode Jp=0.53 A/cm^2**
  - **Spectrolab high Eg diode did not current limit at 500X**

Anticipated Issues for Success of Lattice-Mismatched Cells

- Lattice-matching of top cell to middle cell
  - Tensile strain can cause severe wafer bowing with 140um thick Ge used for space solar applications.
  - High resolution asymmetric bragg x-ray diffraction is necessary for proper matching of solar cell active layers.
- Reproducibility of InGaAs misfit dislocation network
- Impact of misfit/threading dislocations on $In_xGa_{1-x}P$ bulk properties such as minority carrier lifetime is unknown.

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Project Milestone Chart

Task	(Months after start of program) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Year 1	Δ											∇												
1. Performance Modeling	Δ			∇																				
2. Mask Design				Δ																				
3. Buffer Layer		Δ					∇																	
4. InGaAs Subcell				Δ					∇															
5. Tunnel Diodes								Δ			∇													
Year 2													Δ											∇
1. InGaP Subcell										Δ					∇									
2. Device Integration													Δ					∇						
3. AR Coating															Δ									
4. Contact Metallization															Δ	∇								
5. Concentrator System																Δ								∇
Final Report																								Δ
Monthly Technical & Financial Reports	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	
NREL Annual Review (TBD)																								

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13. ABSTRACT *(Maximum 200 words)*

- The High Performance Photovoltaic Project held a Kickoff Meeting in October, 2001. This booklet contains the presentations given by subcontractors and in-house teams at that meeting. The areas of subcontracted research under the HiPer project include Polycrystalline Thin Films and Multijunction Concentrators. The in-house teams in this initiative will focus on three areas: 1.) High-Performance Thin-Film Team-leads the investigation of tandem structures and low-flux concentrators, 2.) High-Efficiency Concepts and Concentrators Team-an expansion of an existing team that leads the development of high-flux concentrators, and 3.) Thin-Film Process Integration Team-will perform fundamental process and characterization research, to resolve the complex issues of making thin-film multijunction devices.

14. SUBJECT TERMS
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